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QUANTITATIVE FRACTIONATION OF ORGANIC PHOSPHORUS COMPOUNDS IN SOME ALBERTA SOILS[1]

R. L. THOMAS AND D. L. LYNCH[2]
University of Alberta, Edmonton, Alberta

[Received for publication December 31, 1959]

ABSTRACT

Soil samples from the A and B horizons of nine virgin profiles and from the A_2 horizons of two of the profiles were analysed for organic phosphorus content. The nine profiles represented five of the major soil zones of Alberta. Organic phosphorus extracted with HCl and NaOH treatments was separated into three fractions using an anion exchange column. The three fractions contained unidentified phosphorus compounds, meso-inositol hexaphosphate and a supposed isomer of meso-inositol hexaphosphate respectively.

The unidentified compounds in the A horizons contained the major proportion of the organic phosphorus. Of the two inositol hexaphosphate compounds measured, the supposed isomer was present in larger quantities than the meso form with the exception of the Hemaruka soil in which the meso form was slightly higher. The three fractions together accounted for only 54.0 per cent of the total organic phosphorus.

The largest amounts of organic phosphorus in the B horizons also occurred in Fraction 1. However, in the B horizons this fraction accounted for 63.4 per cent of the total organic phosphorus in comparison to the 42.2 per cent in the first fraction of the A horizons. The total of the two inositol hexaphosphate compounds in the B horizons accounted for only 2.8 per cent of the total organic phosphorus while in the A horizons the same compounds accounted for 11.8 per cent of the total organic phosphorus. Of the 2.8 per cent organic phosphorus that was present as inositol hexaphosphate in the B horizons, the greatest proportion was in the meso form, while the reverse was true of the A horizons.

The A_2 horizons contained 6.9 per cent of the total organic phosphorus in the inositol hexaphosphate form, with the larger amount in the meso form.

INTRODUCTION

Earlier investigations of the phosphorus content of Alberta soils (8, 9, 11) have dealt mainly with the inorganic phosphorus fraction. Odynsky (11) fractionated the inorganic compounds on the basis of solubility but did not attempt to separate the organic phosphorus fraction that he extracted. He reported that organic phosphorus made up to 76 per cent of the total phosphorus in the soils investigated.

A number of methods have been proposed for the separation of organic phosphorus compounds. Bower (3) used chemical fractionation to isolate phytin and its derivatives. By this method phytin or inositol hexaphosphate was found to account for 26 per cent to 35 per cent of the total organic phosphorus. The derivatives of phytin, containing less than six phosphate groups, accounted for up to 14 per cent of the total organic phosphorus. Pederson (12), using a modified technique, reported that inositol hexaphosphate made up to 46 per cent of the total organic phosphorus.

[1]Contribution from the Department of Soil Science, University of Alberta, Edmonton, Alta.
[2]Research Assistant, and Assistant Professor of Soil Science, respectively.

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[1]Contribution from the Department of Soil Science, University of Alberta, Edmonton, Alta.
[2]Research Assistant, and Assistant Professor of Soil Science, respectively.

Paper chromatography was utilized by Anderson (1, 2) to identify and estimate inositol hexaphosphate compounds. He was able to estimate that approximately one-third of the organic phosphorus was in the inositol-hexaphosphate form. Traces of inosital triphosphate and tetraphosphate were also found.

Smith and Clark (13, 14) introduced an anion exchange column procedure to separate inositol hexaphosphate from other phosphorus compounds. This procedure was modified by Caldwell and Black (4, 5, 6) and used to estimate the inositol hexaphosphate content in soils and its synthesis by micro-organisms. They found an average of 17 per cent of the organic phosphorus was in the form of inositol hexaphosphate. Although the inositol-hexaphosphate phosphorus ranged from 3 per cent to 52 per cent of the total organic phosphorus only 4 of the 49 soils analysed had an inositol-hexaphosphate phosphorus content as high as the 30 per cent of total organic phosphorus reported by Anderson (2).

The present study was undertaken to determine the inositol hexaphosphate content of a number of Alberta soils and to compare the values found with those reported for similar investigations in other places.

MATERIALS AND METHODS

The A and B horizons of the nine virgin profiles described in Table 1, representing five of the soil zones of Alberta, were sampled. Samples were also obtained from the A_2 horizons of two of the profiles where this horizon was sufficiently developed to permit sampling. The total organic phosphorus content was determined by the method of Mehta *et al.* (10). The procedure for the extraction and separation of the organic phosphorus compounds is adequately described elsewhere (3, 4, 5). However, the general procedure includes an initial extraction of the soil with concentrated HCl followed by a cold (20°C.) and a hot (90°C.) 0.5 N NaOH extraction.

TABLE 1.—DESCRIPTION OF SOILS

Soil Series	Soil Zone	Description
Breton loam	Grey Wooded	Orthic grey wooded profile developed on glacial till from the Paskapoo formation.
Falum loam	Degraded Black	Orthic profile developed on glacial till.
Beaverhills loam	Black	Orthic profile developed on glacial till from the Edmonton formation.
Malmo loam	Black	Solodic profile developed on lacaustrine clay.
Camrose loam	Black	Solonetz to solodized solonetz profile developed on glacial till from the Edmonton formation.
Wetaskiwin loam	Black	Solodized solonetz profile developed on lacaustrine clay.
Hemaruka loam	Brown	Solonetz to solodized solonetz profile developed on glacial till from the Bearpaw formation.
Chin loam	Brown	Orthic profile developed on alluvial lacaustrine material.
Unnamed loam	Dark Brown	Orthic profile developed on non-saline resorted glacial till.

After the humic acid was removed from the alkali extract the acid and alkali solutions were combined and adjusted to a pH of 1.8 which precipitated the inositol hexaphosphate as the ferric salt. This precipitate was dissolved in 0.85 N HCl and adsorbed on a De-Acidite* anion exchange resin column 14 centimetres long and 1.1 centimetres in diameter. The organic phosphorus material was then eluted from the column in three fractions of 500 millimetres, 250 millimetres, and 250 millimetres using 0.85 N HCl, 1.40 N HCl and 3.0 HCl respectively as the eluting solutions for the three fractions. The organic phosphorus in Fraction 1 is supposedly inositol with less than six phosphorus groups plus other organic phosphorus compounds. Fraction 2 contains meso-inositol hexaphosphate while Fraction 3 contains a compound that is supposed to be an isomer of meso-inositol hexaphosphate.

The phosphorus determinations were made by digesting appropriate aliquots with 1 or 2 millimetres of 72 per cent perchloric acid. After digestion and neutralization with 1:1 ammonium hydroxide using p-nitrophenol as an indicator, phosphorus was determined by the method of Dickman and Bray (7) using concentrated $SnCl_2$ as a reducing agent as suggested by Mehta *et al.* (10).

Soil reaction was determined on a 1:1 soil-water mixture with a Beckman model H-2 glass electrode pH meter and organic matter content by the modified wet combustion procedure of Walkley Black (15).

RESULTS AND DISCUSSION

Content of Inositol Hexaphosphate

The results of the analyses of the A horizons and the two A_2 horizons are summarized in Table 2. The inositol-hexaphosphate phosphorus in the A horizons ranged from 9.0 μg per gram in the Chin soil to 155.8 μg per gram in the Wetaskiwin soil with the average for the nine soils of 54.5 μg per gram. As a percentage of the total organic phosphorus the inositol hexaphosphate values represent a range from 2.2 per cent to 21.9 per cent and in the nine soils accounted for only an average of 11.8 per cent of the total organic phosphorus. While the range of inositol hexaphosphate was greater than that obtained by Caldwell and Black (6) (from 4 μg to 98 μg per gram with an average of 39 μg per gram), the average content expressed as a percentage of the total organic phosphorus was somewhat less than the 17 per cent they reported and considerably below the value of 30 per cent reported by Anderson (2).

Of the 49 soils analysed by Caldwell and Black (6), only 10 were virgin profiles. The inositol-hexaphosphate phosphorus in these samples ranged from 28.1 μg to 84.9 μg per gram of soil with an average of 55.9 μg per gram. The actual amounts of inositol hexaphosphate compared favourably with the amount found in the Alberta soils, although the range was not as great. However, if the Iowa values are expressed as a percentage of the total organic phosphorus, a range of 7.9 per cent to 24.8 per cent with an average of 15.5 per cent was obtained. This range would include most of the Alberta soils but the average content of 15.5 per cent was substantially

*Weakly basic aliphatic polyamine resin obtained from the Permutit Co., New York, N.Y.

TABLE 2.—THE AMOUNT AND PER CENT OF INOSITOL HEXAPHOSPHATES, TOTAL ORGANIC PHOSPHORUS, pH AND PER CENT ORGANIC MATTER IN THE A AND A_2 HORIZONS OF SEVERAL ALBERTA SOILS

Soil series	Organic phosphorus μg/gram					Inositol hexaphosphate phosphorus as per cent of total organic phosphorus	Meso-inositol hexaphosphate as per cent of total inositol hexaphosphate	pH	Per cent organic matter
	Fraction No.			Total inositol hexaphosphate	Total organic phosphorus				
	1 *	2 Meso-inositol hexaphosphate	3 Supposed isomer of meso-inositol hexaphosphate						
Breton A	170.4	14.8	15.6	30.4	414	7.3	48.7	5.5	8.2
Falum A	189.1	22.9	41.9	64.8	423	15.3	35.3	6.3	8.0
Beaverhills A	215.8	15.0	17.0	32.0	308	10.4	46.9	7.1	4.9
Malmo A	314.0	24.9	42.4	67.3	673	10.0	37.0	6.1	13.6
Camrose A	237.5	28.3	43.6	71.9	628	11.4	39.4	5.9	9.8
Wetaskiwin A	318.3	72.4	83.4	155.8	710	21.9	46.5	5.7	11.1
Hemaruka A	84.5	8.4	8.0	16.4	148	11.1	51.2	6.1	2.4
Chin A	71.4	6.2	2.8	9.0	413	2.2	68.9	5.7	8.2
Unnamed A	149.9	18.4	24.7	43.1	434	9.9	42.7	5.8	8.1
Av.	194.5	23.5	31.0	54.5	461	11.8	43.1		
Breton A_2	92.8	5.2	2.1	7.3	111	6.6	71.2	5.3	0.7
Falum A_2	51.3	5.9	2.0	7.9	109	7.2	74.7	5.8	1.0
Av.	72.0	5.6	2.1	7.6	110	6.9	73.7		

*Fraction 1 is the material collected in the 500-ml. fraction that is eluted with 0.85 N HC1. It is supposedly inositol with less than six phosphate groups and other organic phosphorus compounds.

higher than the 11.8 per cent found in the Alberta soils. If the surface horizon samples of Caldwell and Black (6) can be compared to the A horizons of this study, then a significant difference in the ratio of inositol hexaphosphate to total organic phosphorus in the surface layers of the two groups is apparent.

The Breton and Falum soils were the only soils that had A_2 horizons that were developed well enough for sampling. A comparison of these two samples with their corresponding A horizons showed some marked differences, i.e., the content of inositol hexaphosphate was much higher in the A horizon than in the A_2 horizons. The inositol-hexaphosphate phosphorus as a per cent of total organic phosphorus was almost the same for the two horizons in the Breton soil. The Falum soil, however, had 15.3 per cent of the total organic phosphorus in the A horizon in the inositol-hexaphosphate form while the A_2 horizon had a corresponding value of only 7.2 per cent. This seems to indicate that either there is an inherent difference in the organic matter of the two horizons or that the inositol hexaphosphate of the A_2 horizon had decomposed faster or had been leached out.

The analyses of the B horizons are summarized in Table 3. The content of inositol-hexaphosphate phosphorus was much lower in the B horizons than it was in the A horizons. The average phosphorus content in the inositol-hexaphosphate form in the B horizon was 4.5 μg per gram and in the A horizons it was 54.5 μg per gram. The most significant comparison, however, appears to be the relationship of inositol-hexaphosphate phosphorus to total organic phosphorus. In the A horizons the inositol-hexaphosphate phosphorus averaged 11.8 per cent of the total organic phosphorus but in the B horizon the phosphorus in the inositol-hexaphosphate form averaged only 2.8 per cent of the total organic phosphorus. From this comparison it appears that there is a considerable difference in the kind of organic phosphorus compounds in the A and B horizons of these soils.

Relation Between Fractions of Organic Phosphorus

The material collected in Fraction 1 was of undetermined nature. It was assumed by Caldwell and Black (4) to be inorganic phosphorus and inositol with less than six phosphate groups attached to it. In this investigation the solution from Fraction 1 did not contain measurable amounts of phosphorus before digestion with perchloric acid. Since considerable amounts were measured after digestion it must be assumed that the phosphorus present in this fraction was of an organic nature. Generally a good deal of difficulty was encountered in obtaining good duplication between phosphorus determinations conducted on the solution from Fraction 1. This could be an indication that some of the compounds in this fraction were fairly complex. Paper chromatography indicated the presence of several organic phosphorus compounds in this fraction.

The organic phosphorus material in Fraction 2 was considered to be meso-inositol hexaphosphate while the third fraction contained a supposed isomer of meso-inositol hexaphosphate. The ratios of these two compounds

TABLE 3. — THE AMOUNT AND PER CENT OF INOSITOL HEXAPHOSPHATES, TOTAL ORGANIC PHOSPHORUS, pH AND PER CENT ORGANIC MATTER IN THE B HORIZONS OF SEVERAL ALBERTA SOILS

Soil series	Organic phosphorus μg/gram					Inositol hexaphosphate phosphorus as per cent of total organic phosphorus	Meso-inositol hexaphosphate as per cent of total inositol hexaphosphate	pH	Per cent organic matter
	Fraction No.			Total inositol hexaphosphate	Total organic phosphorus				
	1 *	2 Meso-inositol hexaphosphate	3 Supposed isomer of meso-inositol hexaphosphate						
Breton B	62.7	3.9	0.8	4.7	81	5.8	83.0	5.0	0.7
Falum B	49.2	2.4	0.6	3.0	70	4.3	80.0	6.0	0.6
Beaverhills B	102.0	1.6	1.3	2.9	144	2.0	55.2	7.7	1.0
Malmo B	117.2	2.8	1.0	3.8	202	1.9	73.7	7.1	2.0
Camrose B	127.8	2.5	2.6	5.1	197	2.6	49.0	6.6	2.0
Wetaskiwin B	100.3	3.1	1.0	4.1	158	2.6	75.6	7.1	2.1
Hemaruka B	112.5	1.4	0.4	1.8	127	1.4	77.8	8.5	1.6
Chin B	92.4	3.4	1.1	4.5	149	3.0	75.6	6.6	1.6
Unnamed B	159.8	4.1	6.3	10.4	333	3.1	39.4	5.9	3.0
Av.	102.7	2.8	1.7	4.5	162	2.8	62.2		

*Fraction 1 is the material collected in the 500-ml. fraction that is eluted with 0.85 N HC1. It is supposedly inositol with less than six phosphate groups and other organic phosphorus compounds.

from the A and B horizons were considerably different. In the A horizons the meso-inositol hexaphosphate ranged from 35.3 per cent to 68.9 per cent and averaged 43.1 per cent of the total inositol hexaphosphate while in the B horizons the range of meso-inositol hexaphosphate was 39.4 per cent to 83.0 per cent of the total inositol hexaphosphate and the average was 62.2 per cent. According to Caldwell and Black (5) the supposed isomer of meso-inositol hexaphosphate is synthesized only by micro-organisms. Therefore a possible explanation of the much lower content of the isomer in the B horizons could be that conditions in the B horizon were not suitable for the growth of the micro-organisms responsible for the synthesis of the isomer.

A general consideration of all three fractions indicated that with this procedure there was a marked difference in the organic phosphorus compounds of the A and B horizons. In the A horizons the first fraction contained an average of 42.2 per cent of the total organic phosphorus and the second and third fractions together contained 11.8 per cent of the total organic phosphorus. This procedure, therefore, has separated 54.0 per cent of the total organic phosphorus in the A horizons. In the B horizons, the first fraction contained an average of 63.4 per cent of the total organic phosphorus while the second and third fractions contained 2.8 per cent accounting for 66.2 per cent of the total organic phosphorus. Therefore the present procedure must have lost more of the organic phosphorus from the A horizons in extraction and purification than was lost in the same steps with the B horizons, or the efficiency of removing these compounds from the two horizons by the present procedure varied considerably.

The fairly large amount of phosphorus compounds in the first fraction that have not been identified emphasizes the need for further research in this area.

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The authors wish to acknowledge the assistance of J. F. Dormaar for the total organic phosphorus analyses.

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THE EFFECT OF DRAINAGE CONDITION ON THE REDOX POTENTIAL, LEACHATE COMPOSITION AND MORPHOLOGICAL CHARACTERISTICS OF A SOIL PARENT MATERIAL STUDIED IN THE LABORATORY[1]

J. A. McKeague[2] and C. F. Bentley[3]

[Received for publication December 10, 1959]

ABSTRACT

Plastic columns containing a calcareous clay loam soil parent material with and without ground aspen leaves at the surface were maintained under different drainage conditions for 32 months. Distilled water was added at regular intervals. Results of redox potential (Eh) measurements at four depths, leachate analysis and analysis of the soil material are presented.

With water table to the surface and a layer of surface leaves, low Eh readings and appreciable iron movement resulted. In a column with fluctuating water table and surface leaves, raising the water table brought about a decrease in the Eh of the soil below the water table. Height of water table had no effect on the Eh of a column which had no leaves at the surface. In columns where the soil material was mixed with quartz sand, leaching brought about marked downward movement of silt and clay size particles. Apart from the removal of soluble salts, there was little measurable change in columns which had no admixture of sand.

INTRODUCTION

During recent years there has been an increasing application of the approach to soil genesis investigations which involves the study of soil material subjected to controlled conditions in the laboratory. The work of Bloomfield (3, 4, 6, 7), Atkinson and Wright (2), Thorp *et al.* (14) among others indicates the promise of this approach in contributing to an understanding of the mechanisms involved in the development of soil profiles.

The purpose of the work reported here was to obtain information in the laboratory concerning the effects of different drainage conditions and the presence or absence of surface leaves on the redox potential and morphology of a soil parent material, and on the composition of the leachate from this material. Such information should be helpful in the study of field profiles formed under various drainage conditions.

MATERIALS AND METHODS

Preparation of Columns

The soil used was a calcareous clay loam till parent material from the Alberta-Saskatchewan boundary near Lloydminster. After air drying, the material was ground to pass a 2-mm. sieve. The thoroughly mixed soil was poured into six rectangular plastic columns. Two other columns were filled with a mixture of soil and quartz sand. One of these columns contained 1000 grams of soil plus 6250 grams of sand and the other contained 400 grams of soil plus 7250 grams of sand. A half-inch layer of quartz sand ensured good drainage from the hole in the base of each column. The columns, which measured 4 x 5 x 20 inches inside, were made from ¼-inch transparent plastic. They had four ½-inch holes at 4-inch intervals down one side. The side holes, normally closed with rubber stoppers, were intended to make possible pH measurements. Platinized platinum electrodes

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prepared as outlined by Quispel (12) were inserted in duplicate to depths 1, 5, 9, and 15 inches from the surface of the soil. They remained there throughout the experiment for Eh measurements. Figure 1 illustrates the design of the columns which were covered with brown paper to discourage the growth of algae.

Treatments of Columns

Treatments of the various columns are tabulated below:

Column	Material	Drainage Condition	Surface Material
1	Clay loam	Saturated to surface	Aspen leaves
2	Clay loam	Alternating water table at 9 inches for 4 weeks then free drainage for 4 weeks	Aspen leaves
3	Clay loam	Water table at 18 inches	Aspen leaves
4	Clay loam	Free drainage	Aspen leaves
5	Clay loam	Alternating water table at 9 inches for 4 weeks then free drainage for 4 weeks	Glass wool
6	Clay loam	Free drainage	Glass wool
7	Clay loam and sand (86%)	Water table at 18 inches	Aspen leaves
8	Clay loam and sand (95%)	Free drainage	Aspen leaves

The water tables were maintained at the depths indicated by placing the columns in plastic or Pyrex vessels of sufficient depth and adding distilled water to the vessels to bring the water tables to the desired levels.

Ground leaves were added to Columns 1, 2, 3, 4, 7 and 8 three or four times a year in order to maintain an organic layer at least a half-inch in depth. Total weights of air dry leaf material added to the columns were: Column 1 — 100 grams; Columns 2, 3 and 4 — 150 grams; Columns 7 and 8 — 110 grams. Each week a litre of water was added in four additions to Columns 2 to 8. Column 1 was kept saturated except for 2 hours each week when the stopper in the base was removed and leachate was collected. Leachates, together with the water added to maintain the water table, were collected from the containers at the bases of the columns each week and collections from successive 4-week periods were consolidated for analysis. After 32 months of leaching the columns were allowed to dry before being sampled for analysis.

Methods of Analysis

Redox potentials were measured with a Beckman model H2 pH meter with a saturated calomel electrode as reference electrode. The calomel electrode was inserted into the surface of the soil in the columns. Attempts to measure pH's by insertion of a glass electrode into the side holes of the columns were unsuccessful and Eh's are, therefore, reported without correction to a standard pH.

Leachates from the columns were analysed as follows. Organic matter was destroyed in an aliquot of the leachate by digesting it with an HNO_3 – $HClO_4$ mixture. The residue was taken up in two successive

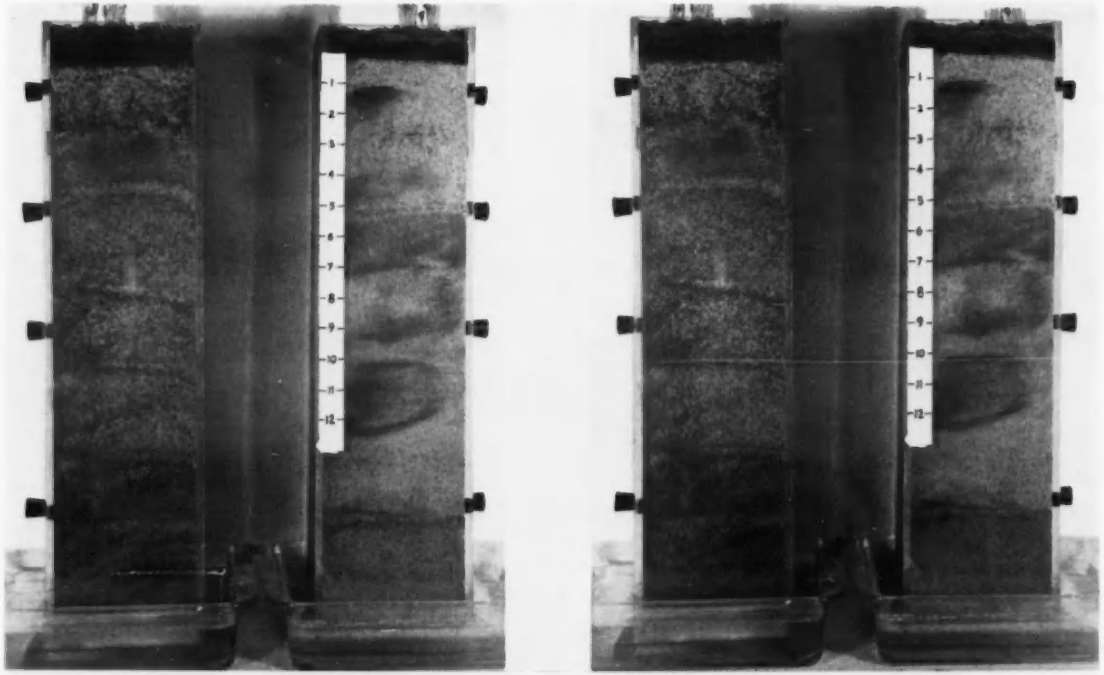

FIGURE 1. Columns 7 (*left*) and 8 (*right*) after 15 months of leaching showing bands of accumulated fine materials.

portions of concentrated HCl and evaporated to dryness. Residues were then dissolved in 1N HCl, filtered and made up to volume. A Beckman DU spectrophotometer with a model 9200 flame attachment and photomultiplier was used for sodium and potassium determinations. Calcium was determined by $KMnO_4$ titration after precipitation as CaC_2O_4. Magnesium in the supernatant solution was determined by titration with EDTA. Iron was determined colorimetrically as ferrous o-phenanthroline. Sulphate was determined tubidimetrically after precipitation as $BaSO_4$. Determinations of carbonate, bicarbonate, and chloride were made on aliquots of the original leachates according to methods outlined in U.S.D.A. Handbook 60 (15).

The procedure for analysis of the soil material after leaching is outlined below. Four or five samples were taken at increasing depths in the columns. These samples were dried and ground to pass a 2-mm. sieve. Inorganic carbon was determined by the A.O.A.C. method (1) modified by using a magnetic stirrer to mix the soil and HCl. Free iron was determined by the method described by Mackenzie (10) except that the colour was developed with o-phenanthroline. Soluble salt analyses were done according to the procedure outlined in Handbook 60 (15). Mechanical analysis of the soil used to fill the columns was done by a pipette method after removal of $CaCO_3$ with 0.2 N HCl. Samples from Columns 7 and 8 were treated with H_2O_2 and HCl before dispersion and were then passed through a 300-mesh sieve to separate the sand. For these columns, sand and silt plus clay were determined gravimetrically.

RESULTS AND DISCUSSION

Visible Changes in Soil Columns

After a month of saturation, Column 1 was a duller grey colour than any of the other columns. Later, further evidence of gleying became visible in the form of dark grey blotches and yellowish brown streaks. However, the chroma of Column 1 did not decrease by more than one

TABLE 1.—SOME ANALYTICAL DATA FOR COLUMNS 7 AND 8 AFTER 32 MONTHS OF LEACHING

Column	Depth	pH	$CaCO_3$ %	Free Fe_2O_3 %	Sand %	Silt + Clay %
7	0—0.5 in.	7.5	0.2	0.05	98.3	1.5
7	0.5—2.5 in.	8.1	0.4	0.10	96.2	3.6
7	2.5—8 in.	8.3	0.6	0.14	93.7	6.0
7	8—14 in.	8.5	0.8	0.16	93.6	6.1
7	14—18 in.	8.5	0.8	0.15	91.8	7.9
7	Parent material (not leached)	8.6	0.95	0.15	91.8	8.2
8	0—1 in.	7.0	0.0	0.02	99.3	0.8
8	1—4 in.	8.0	Trace	0.05	98.2	1.8
8	4—9 in.	8.4	0.2	0.07	97.8	2.1
8	9—15 in.	8.6	0.3	0.07	97.6	2.5
8	15—18 in.	8.6	0.3	0.06	97.8	2.2
8	Parent material (not leached)	8.6	0.36	0.06	96.8	3.2

Munsell unit during the course of the experiment except in the blotched area. The column did not develop the appearance of gley as described by Joffe (9).

The permeability of Columns 5 and 6, which did not have leaves at surface, decreased from 1 inch per hour initially to 1 inch in 24 hours after 2 years of leaching. The soil material at the surface of these columns developed a massive appearance. Permeability of the other columns, which had a layer of leaves at the surface, remained relatively constant at 1 inch per hour. In the latter columns the surface material maintained a weak granular structure. It is probable that products of leaf decomposition and/or products of bacterial action had an aggregating effect upon the surface soil in columns which had surface leaves, thus preventing the development of the adverse physical condition observed in Columns 5 and 6.

After 3 months of leaching it was apparent that the soil material in Columns 7 and 8 was moving downward and accumulating in irregular bands. Figure 1 shows these columns after 15 months of leaching. The discontinuous bands of fine material are quite apparent, especially in Column 8.

COLUMN CHANGES DETERMINED BY ANALYSES

Mechanical Composition

Table 1 presents data for the changes in composition resulting from 32 months of leaching Columns 7 and 8. These data show that in Columns 7 and 8 silt and clay-sized particles were moved downward. There was some removal of fine particles from the columns as for both columns the percentage of silt and clay in the parent material is higher than that in any layer sampled. A subsequent experiment involving leaching of a soil-sand mixture with and without surface leaves indicated that the leaves were not responsible for translocation of fine particles since equal downward movement of fine particles occurred in columns with and without surface leaves. Thus, under the conditions maintained in the columns, the physical action of water appears to be primarily responsible for the translocation of silt and clay. A rather similar movement of fine particles in soil columns

TABLE 2.—DUPLICATE Eh READINGS TAKEN AT FOUR DEPTHS IN EACH SOIL COLUMN AFTER 10 MONTHS OF LEACHING (EXPRESSED IN MV.)

Depths	Col. 1	Col. 2[1]	Col. 3	Col. 4	Col. 5[1]	Col. 6	Col. 7	Col. 8
1 in.	−230	610	710	660	640	650	640	620
	−130	590	650	660	650	650	610	620
5 in.	−180	150[2]	570	670	610	580	620	590
	−180	590	620	640	650	590	640	620
9 in.	−180	560	690	680	590	660	620	650
	−190	560	700	660	670	590	660	640
15 in.	−130	630	690	700	650	640	580	650
	−160	580	690	690	660	670	660	650

[1] Readings taken during a period of free drainage.
[2] This electrode reading was consistently low; explanation unknown.

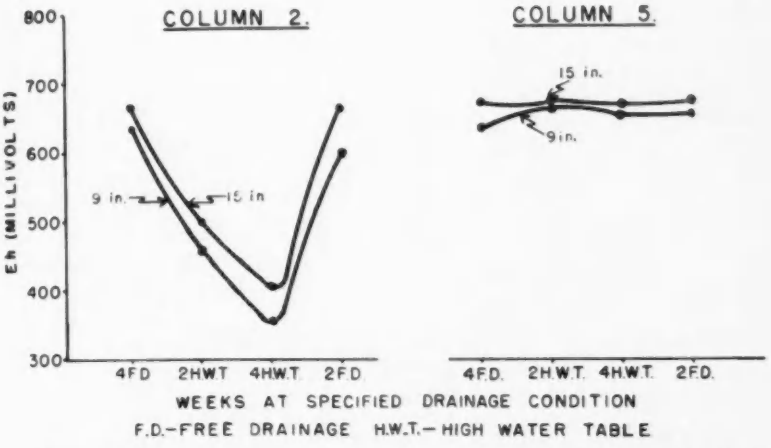

FIGURE 2. Effect of fluctuating water table on the Eh's below the water table in Column 2 (leaves on surface) and Column 5 (glass wool on surface).

leached with water has been reported by Henin and Betremieux (8) and Thorp *et al.* (14).

The data of Table 1 also show that the treatments used brought about decreases in pH, $CaCO_3$ equivalent and free Fe_2O_3 in the uppermost layers of Columns 7 and 8.

Redox Potentials

The trends for Eh of the various columns were apparent after the first month and Eh readings became quite stable after a few months. Table 2 shows average readings of duplicate electrodes after 10 months of leaching. The data show that Column 1 (saturated) was under strongly reducing conditions while the other columns were under oxidizing conditions. Thus the glei-like colour of Column 1 was associated with low Eh.

Figure 2 compares the effect of fluctuating water table on Column 2 (leaves on surface) and Column 5 (glass wool at surface). A high water table had no effect upon the Eh of Column 5 but it resulted in marked lowering of the Eh below the water table in Column 2.

The redox potential data are in general agreement with those of Starkey and Wight (13) who showed that low Eh in soil results from a combination of water-logging and the presence of organic matter. Eh values reported in Table 2 and Figure 2 are within the range of those reported by others who used similar methods of measurement (11, 12, 13).

Since Eh apparently reflects the drainage condition of the soil in the presence of organic matter, field Eh measurements may be useful in distinguishing soils of different drainage states. For example, visual evidence of drainage state may be misleading because calcareous soils usually do not show drab grey or bluish gley colours as strongly as non-calcareous soils. Furthermore, the colour of a poorly drained profile is influenced by the colour of its parent material. Bloomfield (3, 4) indicated that the drab

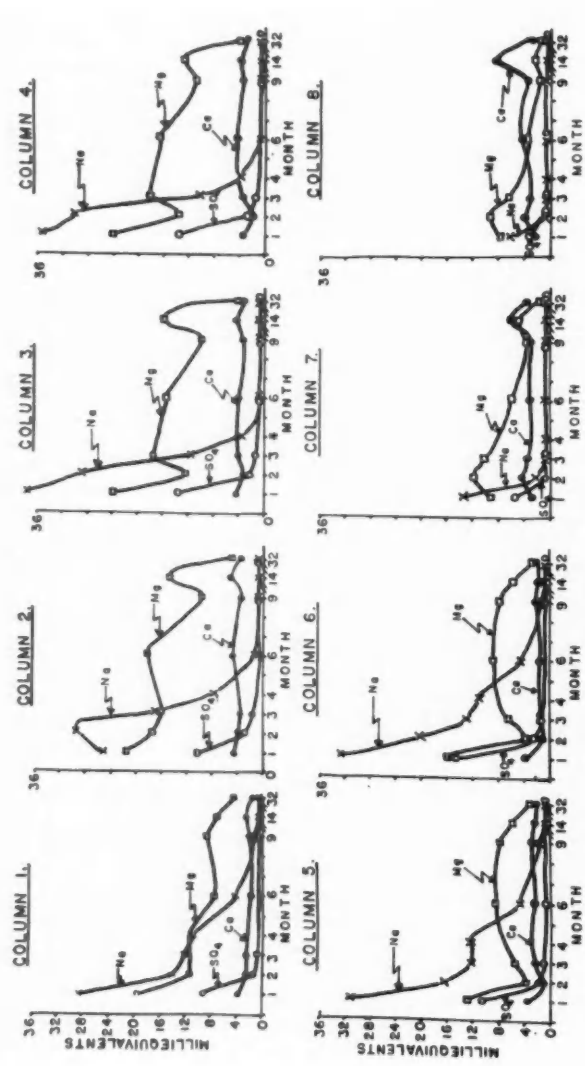

FIGURE 3. Composition of leachates from soil columns, expressed as m.e. removed per 4 weeks.

colour of gleyed soil is due to the removal of iron oxide coatings on soil particles. He also showed (5) that a gley horizon may be high in free iron due to periodic aeration and oxidation of ferrous iron. Thus, free iron analysis may be of little use in differentiating soils of different drainage states. Field Eh measurements made over a period of several weeks in the spring and summer should show the duration and intensity of reducing conditions in the soil. This would provide objective information which together with field observations would be useful in separating and classifying Gleysolic soils.

Leachate Composition

Figure 3 presents analytical data for the acid treated leachates from the columns. The rate of leaching out of sodium and sulphate from the columns decreased rapidly to a very low value. The magnesium content of the leachates generally decreased with time while the calcium content remained low and relatively stable. In Columns 7 and 8 (with added sand) calcium content of the leachates increased after 12 months of leaching.

Comparison of the graphs in Figure 3 reveals some differences in leachate composition due to various treatments of the soil columns:

The removal of calcium and magnesium from Column 5 and 6 (no surface leaves) was slower than that from Columns 2, 3, and 4 (surface leaves). Surface leaves had little apparent effect upon rate of removal of sodium and sulphate. This suggests that leaf decomposition products played a part in the removal of calcium and magnesium from the soil columns while the solution action of water alone was responsible for the removal of sodium and sulphate.

The removal of ions from Column 1 (saturated) was slower than that from Columns 2, 3, and 4. This was probably due to the smaller quantity of leachate which passed through Column 1 each week.

Leachates from Columns 7 and 8 were generally lower in content of magnesium, sodium, and sulphate than were leachates from the other columns. This was no doubt due to the dilution of the clay loam material with sand in Columns 7 and 8 and hence the reduction in soluble materials in these columns. However, the calcium content of leachates from Columns 7 and 8 was often greater than that of Columns 5 and 6 which had no surface leaves. Apparently there was an abundance of a somewhat soluble calcium compound or compounds — probably carbonate — even in Column 8 (95 per cent sand). The enhancing effect of materials leached from surface leaves upon removal of this calcium is apparent.

Inspection of the analytical data for leachates revealed that leaf additions affected removal of calcium and magnesium from the columns as illustrated by the data in Table 3.

There was a similar increase in the calcium and magnesium content of the leachates from Columns 2, 4, and 7 after an addition of ground

TABLE 3.—REMOVALS PER 4-WEEK PERIOD (TOTAL AMOUNT IN LEACHATES)

Weeks since the previous addition of leaves	Column 3		Column 8	
	Ca m.e.	Mg m.e.	Ca m.e.	Mg m.e.
1	5.4	15.7	8.9	2.3
24	4.6	9.6	4.8	1.0
1	7.6	15.9	8.6	2.0

TABLE 4.—IRON CONTENT OF LEACHATES FROM COLUMNS FOR SELECTED PERIODS
(mg. per column per 4 weeks)

Time, weeks	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
0-4	3.7	0.9	0.2	0.3	0.1	0.1	0.7	1.2
28-32	4.3	0.3	0.2	0.1	0.2	0.2	0.2	0.2
56-60	2.4	0.2	0.1	0.1	0.2	0.1	0.2	0.5
82-86	1.6	0.2	0.2	0.1	0.3	0.1	0.2	0.2
112-116	0.3	0.2	0.2	0.1	0.2	0.1	0.1	0.2

TABLE 5.—POTASSIUM CONTENT OF LEACHATES FROM COLUMNS FOR SELECTED PERIODS
(m.e. per column per 4 weeks)

Time, weeks	Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8
0-4	0.8	0.9	1.5	1.4	1.3	1.2	0.8	0.7
28-32	0.3	0.8	0.8	0.9	0.8	0.9	0.4	0.3
124-128	0.2	0.6	0.6	0.4	0.2	0.2	0.3	0.2

aspen leaves. Because of this effect, the data shown in Figure 3 are, wherever possible, for periods of 8 weeks or more after the addition of leaves. When 10 grams of ground leaves alone were leached, removal of calcium, magnesium, potassium and sulphate during the first 4-week period was 2.1, 2.1, 1.5 and 0.7 m.e. respectively. Further leaching of ground leaves removed only minor amounts of these ions.

Table 4 shows the iron content of the column leachates for selected 4-week periods. Iron removed from Column 1 (saturated) far exceeded that removed from any other column. Continuous reducing conditions, in conjunction with leachings, evidently increases iron solution and removal. The reason for the marked decrease in iron content of Column 1 leachates is not established. Perhaps most of the readily soluble iron was removed in the early months of the experiment. Iron content of Column 8 (95 per cent sand) leachates averaged somewhat higher than that of columns containing only clay loam – for example, Columns 3 and 4. This may have been due to a reduced adsorption, in the lower part of the column, of iron brought into solution in the upper part of Column 8. Bloomfield (6) has suggested a mechanism to account for such adsorption.

The potassium content of the leachates remained low throughout the experiment. Table 5 illustrates the gradual decline in removal of potassium from the soil columns.

The bicarbonate content of the leachates was measured periodically before they were evaporated. Bicarbonate was the dominant anion in the leachates and the sum of HCO_3^- and SO_4 in m.e. was approximately equal to the sum of Ca^{++}, Mg^{++}, Na^+, and K^+ in m.e.

Analysis of soil samples from Columns 1 to 6 after 32 months of leaching showed only the following changes in the parent material used in the columns:

A decrease in pH in the surface inch of the columns — from 8.6 to 8.0 in Columns 1 to 4 and from 8.6 to 8.3 in Columns 5 and 6.

A decrease in $CaCO_3$ equivalent from 6.9 per cent to 5.8 per cent in the upper inch of Columns 1 to 6.

A decrease in free iron oxide from 1.12 per cent to 1.01 per cent in the upper inch of Column 1. Free iron oxide content remained essentially unchanged in Columns 2 to 6.

Removal of soluble salts.

Although Columns 2 to 8 were leached for 32 months with approximately a foot of water a month, few major changes in composition occurred. Carbonates were not nearly removed even from the column which contained 95 per cent quartz sand. With carbonates still present, little change in other constituents could be expected. This illustrates that drastic means must be employed to achieve much in the nature of profile development in a laboratory experiment. However, this type of approach seems to be valuable for studying some specific aspect or agent of soil development. For example, in the experiment described, the influences of organic matter and drainage condition on redox potential are clearly demonstrated.

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THE EFFECT OF NITROGEN TOP DRESSING ON YIELD AND PROTEIN CONTENT OF NITROGEN-DEFICIENT CEREALS[1]

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ABSTRACT

Top dressings of ammonium nitrate were made during the growing season to crops of barley and oats showing symptoms of acute nitrogen deficiency. The addition of nitrogen in the early stages of plant growth resulted in increased vegetative growth and increased yields. Applications of nitrogen delayed until the shot-blade stage had little effect on yield, but substantially increased the protein content. The yield of protein per acre was increased with higher rates of fertilization, regardless of whether the effect of the added nitrogen was to increase yield or protein content.

INTRODUCTION

One of the agricultural problems of increasing importance in the Prairie Provinces is the appearance of nitrogen-deficiency symptoms in cereal crops during the months of June and July. Crops exhibiting these symptoms are becoming increasingly common in certain regions of Alberta. The experiments described herein were conducted to determine whether or not an application of nitrogen fertilizer after the deficiency symptoms had become apparent would enable the crop to resume normal growth and produce a profitable yield of grain.

A review of the literature shows that considerable work has been done on the application of nitrogen fertilizers to cereal crops during the growing period. Rankin (9) has shown that an application of nitrogen in April to winter wheat produced the greatest number of spikes per row while the largest number of kernels per head was produced when the nitrogen was applied in small increments throughout the growing season. This latter treatment also produced the highest yields. Garner (6) has reported that all top dressings of nitrogen to winter wheat between November and May produced about the same effect on yields. The earlier applications promoted an increase in tillering, while later applications increased the size of the kernels. It was shown by Foot *et al.* (5) that nitrogen produced the largest yield increases when applied to barley either at seeding time or in the very early stages of growth. Later applications up to heading time resulted in progressively smaller and smaller yield increases. Similar results have been found by Hobbs (7) and Smith (10).

It has been shown by Coic (2, 3) that a large application of nitrogen early in the growth of the plant stimulated vegetative growth so much that the later nutrient requirements of the plant were greatly increased. If this larger requirement was not met, a reduction in yield was inevitable.

The protein level of cereals is also affected by nitrogen fertilization. Borowkowski and Kozera (1) have reported that in Poland the highest protein content and the best quality grain were obtained when all the nitrogen fertilizer was applied to oats shortly before heading. In Tennessee, Long and Sherbakoff (8) have shown that delaying until May the application of nitrogen fertilizer to winter wheat resulted in a crop with a

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significantly higher protein content, and of superior milling quality. Similar results have been reported by Coic (2), Garner (6), and Widdowson *et al.* (11). Foliar application of nitrogen in the form of urea sprays has been shown by Finney *et al.* (4) to substantially increase the protein level in wheat. A single spray at flowering time increased the protein level from 10.8 per cent to 15.2 per cent with no lowering of the baking quality, while successive sprays at intervals of 2 to 3 days raised the protein level to 21 per cent.

While this problem has received wide attention elsewhere, little work has been done in Alberta. The increased use of combines, a trend towards maintenance of trash cover on the soil, and a natural decrease in the nitrogen level with continued farming have brought the problem to the fore in recent years.

MATERIALS AND METHODS

Experiments were carried out during the summers of 1957 and 1958 on fields showing the typical chlorotic symptoms of nitrogen deficiency. These fields were located within about 75 miles of Edmonton in north-central Alberta. Each trial consisted of strip-applications of ammonium nitrate fertilizer at rates supplying 20, 40, and 60 pounds of nitrogen per acre. The fertilizer was applied during the last 2 weeks of June and the first 2 weeks of July with a specially constructed spreader. At certain locations in both years a second application was made to adjacent strips of the same fields after an interval of about 2 weeks to determine any difference in the effect of early and later applications. Trials were conducted on 32 fields of barley and 9 fields of oats in 1957, and on 22 fields of barley and 3 fields of oats in 1958.

In the fall, six 1-square-yard samples were taken from each of the fertilized and unfertilized strips. These samples were allowed to cure indoors for about a week, dried, and threshed. The threshed grain from individual samples was weighed for yield determination, and the samples were bulked for laboratory analysis. The bulked grain samples were thoroughly mixed, sub-sampled, and ground to pass a 20-mesh sieve. The nitrogen content was determined by the Kjeldahl method using a commercial catalyst and distilling into 4 per cent boric acid solution. The factor 6.25 was used for conversion of nitrogen content to protein content.

The yield data from each trial were analysed as a randomized block experiment. Since the analyses for protein content were done on bulked samples, no statistical analysis was done on the results.

RESULTS AND DISCUSSION

It was observed that 1 or 2 weeks following the application of nitrogen fertilizer the chlorotic condition of the crop disappeared. The darkness of the green colour produced by the fertilizer was generally proportional to the rate of fertilization. The application of 40 and 60 pounds of nitrogen per acre consistently produced plants with a darker bluish-green colour than did the 20-pound rate. Twenty pounds of nitrogen per acre appeared sufficient in all cases to produce healthy, normal plants.

The utilization of applied nitrogen was greatly dependent on precipitation following application. Observations of the trials were not made at

sufficient intervals to determine the exact time of precipitation, nor the length of time required for the fertilizer to produce an effect on the colour of the plants. Very little use of nitrogen appeared to occur, however, until rain had washed the fertilizer down to the root zone.

Observations made 4 to 6 weeks following the earlier applications showed in many cases an increase in both the height of plant and length of head in the fertilized plots. At several locations, where no differences in height of the crop were noted, the heads were longer and much fuller than those of the check plots. No instances of increased stooling or of second growth were noted.

The late applications of nitrogen fertilizer were found to stimulate weed growth, particularly in those fields which were badly infested with weeds, or where spraying for weed control had not been carried out. Late applications of nitrogen also delayed the maturity of the crop. As all trials had to be harvested before the co-operating farmer was ready to swath his crop, the trials could not be left until maturity. In many cases there was an estimated delay in maturity of from 1 to 2 weeks due to the added nitrogen. It is possible that this delay in maturity may have resulted in a lowering of yields caused by shrinkage of immature kernels. Such an effect, if present, may not have been of great magnitude, since all samples were left to cure about 1 week before being dried and threshed, allowing ample time for the maturation process to continue even though the plants had been cut.

The average yield of grain and the average protein content following top dressings of nitrogen are given in Tables 1 and 2. These data, which are averages following applications made at all stages of growth, show an increase in both yield and protein content which is roughly proportional to the rate of fertilization. The original data show, however, that, for both yield and protein content, there is considerable variability in the results from trial to trial. In general it was found that where large increases in yield were obtained, little or no effect was produced on the protein content,

TABLE 1.—AVERAGE YIELD OF GRAIN (CWT./AC.) FOLLOWING TOP DRESSINGS OF NITROGEN

	Number of trials	Rate of fertilization			
		Check	N_{20}	N_{40}	N_{60}
1957					
Barley	32	10.3	12.8 (8)[1]	13.6 (15)	14.6 (20)
Oats	9	12.5	15.1 (4)	16.9 (6)	19.7 (6)
1958					
Barley	22	8.6	11.4 (16)	12.4 (15)	13.5 (17)
Oats	3	9.7	15.6 (2)	17.3 (3)	20.1 (3)

[1]Figures in brackets indicate number of trials having significant increases over check ($P = 0.05$).

TABLE 2.—AVERAGE PROTEIN CONTENT (PER CENT) OF GRAIN FOLLOWING TOP DRESSINGS OF NITROGEN

	Number of trials	Rate of fertilization			
		Check	N_{20}	N_{40}	N_{60}
1957					
Barley	32	10.3 (8.9-11.9)[1]	11.8 (9.0-14.4)	13.2 (8.6-17.1)	14.2 (8.8-17.4)
Oats	9	10.1	11.6	13.0	13.7
1958					
Barley	22	10.1	11.3	12.9	14.0
Oats	3	9.7	10.8	11.9	13.4

[1]Figures in brackets indicate range of values for 1957 barley. Similar ranges were found for the other crops.

but where the yield was only slightly increased by the added nitrogen, the protein content was substantially increased.

This interaction between yield and protein content can be explained on the basis of the stage of plant growth when the fertilizer became available. If the fertilizer was broadcast at an early date, and rain fell soon thereafter, the nitrogen was utilized by the plants for increased vegetative growth including height of crop, length of head, the number of kernels per head, and consequently an increase in yield. If no rain fell following an early application, or if the application was not made until a late date, with the fertilizer becoming available only in the later stages of plant growth, very little increase in yield occurred since vegetative growth had almost ceased. The kernels were still filling and ripening, however, and the large amount of available nitrogen was effective in increasing the protein content of the grain.

A portion of the original data from selected trials on barley in both 1957 and 1958 are given in Table 3 to illustrate the interaction between yield and protein content. The results reported for trials 57-1 and 58-5 are typical of the data obtained from several trials where the nitrogen top-dressing was made during the third week of June when the crop was generally at about the 4- or 5-leaf stage. These data show increases in yield of well over 100 per cent and only a relatively small effect on the protein content. The decrease in protein content of trial 57-1 with increasing rates of fertilization is not typical of all these trials and was probably caused by a surplus of available nitrogen in the very early stages of development resulting in excess vegetative growth and a subsequent deficiency of nitrogen later in the season. Trials 57-31 and 58-12 are representative of those trials where the top dressing of nitrogen was made during the first 2 weeks of July when the crops were generally in the shot-blade stage. The results of these later applications show very little effect on the yield of grain, but show an increase in the protein content of up to 80 per cent.

The remaining data in Table 3 are from two locations where both early and late applications of fertilizer were made on adjacent strips of the same

TABLE 3.—YIELD AND PROTEIN CONTENT OF SELECTED TRIALS ON BARLEY FOLLOWING TOP DRESSINGS OF NITROGEN, 1957 AND 1958

Trial No.	Yield of grain (cwt./ac)				Protein content (per cent)			
	Check	N_{20}	N_{40}	N_{60}	Check	N_{20}	N_{40}	N_{60}
57-1	8.4	13.2*	16.2*	22.6*	10.1	9.2	8.6	8.8
58-5	6.3	11.2*	14.6*	15.6*	11.6	11.1	11.6	11.6
57-21	6.2	8.0	7.3	7.6	10.6	13.4	16.2	17.4
58-12	4.8	7.0*	5.2	5.0	10.4	13.9	17.8	18.8
57-10 early	11.7	16.8*	17.1*	18.2*	9.9	10.9	11.2	13.4
late	8.8	9.2	10.8	9.1	10.2	14.1	16.1	16.3
58-8 early	9.6	13.8*	14.2*	16.6*	10.0	10.4	11.3	12.7
late	11.0	12.9	14.4	11.0	9.7	11.6	14.0	15.3

*Significant increase over check (P = .05)

TABLE 4.—AVERAGE YIELD OF PROTEIN (LB./ACRE) FOLLOWING TOP DRESSINGS OF NITROGEN

	Number of trials	Rate of fertilization			
		Check	N_{20}	N_{40}	N_{60}
1957					
Barley	32	110	149	175	200
Oats	9	123	169	212	250
1958					
Barley	22	86	127	156	182
Oats	3	92	167	204	265

fields. Again the early applications were made near the 4- or 5-leaf stage and the late applications were made at about the shot-blade stage. These data also illustrate the previously mentioned interaction and, since they are from individual fields, they indicate that the interaction can indeed be attributed to time of application and not to varietal or climatic differences between trials at widely different locations.

In addition to these trials which showed such marked effects, there were others which showed increases in both yield and protein content, but of smaller magnitude than those reported in Table 3. This would appear to be a result of the fertilizer becoming available to the plants at stages of growth intermediate between the 4-leaf and the shot-blade. This in turn was dependent, not only on the date of top dressing, but also on precipitation following the fertilizer application.

The average yield of protein per acre for the two crops in both years is shown in Table 4. These averages show a substantial increase in the yield of protein per acre with increasing rates of nitrogen. The original data show that, despite the variability in both yield and protein content of the grain, there was a consistent increase in the yield of protein per acre with

higher rates of fertilization. The original data also show that in about two-thirds of those trials, where both early and late applications were made in the same field, the early application produced a greater increase in yield of protein than did the late application.

The data presented suggest the usefulness of top dressings of nitrogen fertilizer as a means of increasing the protein content of cereals. An evaluation of the nutritive status of the increased protein has been initiated in order to determine the practical importance of this technique under Alberta conditions.

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A LONG-TERM FIELD EXPERIMENT WITH COMMERCIAL FERTILIZERS AND MANURE

I. Fertility levels and crop yields in a rotation of swedes, oats and hay[1]

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ABSTRACT

In a field experiment, conducted from 1936 to 1957, a rotation of swedes, oats and hay was followed and treatments included commercial fertilizers and manure.

Changes in the chemical composition of the soil during the experiment included significant decreases in soil organic matter, total nitrogen and cation exchange capacity. In no case was the initial content of exchangeable potassium maintained and although changes in adsorbed and easily acid-soluble phosphorus were negligible with a number of treatments only one resulted in a significant increase.

The treatments were applied in the swede year and yield differences with this crop were greater than for either the oats or hay. Data for the latter two crops indicated that with most of the treatments there was a tendency for yields to decline as the experiment progressed. This was not the case with swedes where variation in yields with rotation cycles was greater than it was in the case of oats or hay. There was a considerable residual effect from manure, and phosphorus had a greater effect on yields than either nitrogen or potassium.

INTRODUCTION

A field experiment conducted at the Experimental Farm, Nappan, Nova Scotia, from 1936 to 1957, was designed to compare the value of various commercial fertilizers and manure in a rotation of swedes, oats and hay. When the experiment was established swedes were of major importance as succulent feed for livestock and were in demand for human consumption. In recent years silage has largely replaced root crops as livestock feed although human consumption still provides a sizable market for swedes.

This paper presents data on changes in the chemical composition of soil during the course of the experiment and evaluates treatments applied in terms of crop yields.

LITERATURE REVIEW

Royer *et al.* (5) investigated difference in exchangeable potassium and available phosphorus resulting from various fertilizer practices and prepared a nutrient balance-sheet showing net gains or losses. Net removals of potash for a 30-year period exceeded 350 pounds per acre and in all treatments but one more phosphorus was removed than was added. They also found that addition of manure apparently increased availability of potash and produced superior yields. Hoover (4) studied the residual effect of potash applications on replaceable potassium in Mississippi soils. He concluded that, if applied annually in excess of plant needs, potassium may accumulate in replaceable form in the A horizon. Brage *et al.* (2), reporting on the long-time effect of applying barnyard manure, found adsorbed phosphorus in the soil was markedly increased while the content of acid-soluble phosphorus was raised by a smaller amount. In a long-time soil fertility experiment Terman and Freeman (6) found phosphorus fer-

[1]Joint contribution from the Experimental Farm, Nappan, N.S., (Contribution No. 104), and the Research Station, Kentville, N.S., (Contribution No. 1030), Canada Department of Agriculture.

tilizer to be the most important factor affecting yield trends. Cordukes *et al.* (3), reporting on a long-term soil fertility experiment, found available phosphorus tended to be higher for manured plots than for those receiving commercial fertilizer. Manure was also effective in maintaining crop yields and was indicated to have considerable residual effect.

MATERIALS AND METHODS

The soil in the experimental area is classified as Nappan clay loam (7) and a 3-year rotation of swedes, oats and hay was followed. The area was divided into three sections each of which carried a different crop in the rotation each year. Within each section there were ten ranges of eight plots each which provided four replications of the 20 treatments given in Table 1. Individual plots were 15.2 by 28.5 feet (1/100th acre) and treatments were randomized in each replication. Sections were separated by 20-foot roadways, ranges within sections by 3-foot pathways and plots within ranges by 6-foot pathways.

In 1931 dolomitic limestone at the rate of 3500 pounds per acre was applied to the entire experimental area. Additional limestone was applied to Section 1 at rates of 1500, 2000, 1500 and 4000 pounds per acre in 1943, 1946, 1949 and 1955 respectively and to Section 2 at the rate of 1800 and 2000 pounds per acre in 1944 and 1947. Section 3 received no limestone during the course of the experiment.

All fertility treatments were applied for the swede crop. Fertilizers with the required analysis were compounded from ammonium sulphate, superphosphate and muriate of potash. The fertilizers, which were broad-

TABLE 1.—TREATMENTS APPLIED IN A LONG-TERM FERTILITY EXPERIMENT

Treatment number	Treatment	Application rate
1	0-12-6	750 lb./ac.
2	2-12-6	"
3	4-12-6	"
4	6-12-6	"
5	2-0-6	"
6	2-4-6	"
7	2-8-6	"
8	2-10-6	"
9	2-12-0	"
10	2-12-3	"
11	2-12-9	"
12	2-12-6 + Borax	" + 10 lb./ac.
13	2-12-6	500 lb./ac.
14	2-12-6	1000 "
15	2-12-6	1500 "
16	Manure	10 tons/ac.
17	"	20 "
18	" + 2-12-6	10 tons/ac. + 500 lb./ac.
19	Manure + Superphosphate	10 tons/ac. + 300 lb./ac.
20	No treatment	

Note: In 1948 and thereafter all treatments except No. 12 included borax at the rate of 20 pounds per acre.

TABLE 2.—ANALYSIS OF SOIL SAMPLES COLLECTED IN 1936 AND 1954
(Mean values for 80 samples)

Year sampled	pH		Total nitrogen		Organic matter		Cation exchange capacity		Exchangeable cations					
									Calcium(Ca)		Magnesium(Mg)		Potassium(K)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
			%		%		m.e./100 g.		m.e./100 g.		m.e./100 g.		m.e./100 g.	
1936	5.85	0.24	0.198	0.032	4.17	0.76	11.08	1.95	6.52	1.17	0.64	0.11	0.29	0.06
1954	6.17	0.20	0.155	0.024	3.51	0.78	9.49	1.71	6.08	0.98	1.32	0.15	0.23	0.03
Difference[1]	0.32		0.043		0.66		1.59		0.44		0.68		0.06	

[1]All differences significant

cast by hand and harrowed in, were mixed with sand to increase the volume and thus assure more even distribution. The manure used came from a dairy barn and was well rotted by composting. It was applied on the hay sod in the late fall and ploughed under.

Wilhelmsburger swedes were sown in ridged rows and later thinned to a 12-inch spacing. There were six rows per plot. Yields and samples for dry matter were taken from the four centre rows.

Oats together with a mixture of red clover, timothy and alsike were sown with a conventional drill seeder. Prior to 1948 the oat crop from an entire plot was used in determining yield. In that year and thereafter yields were based on six rod row samples per plot. Hay yields were obtained by cutting an entire plot, weighing the hay on platform scales, and taking two 500-gram samples of chopped forage for the determination of dry matter.

After the experiment was laid out and before any treatments were applied composite soil samples, representative of the 0-6 inch depth and consisting of four borings each, were taken from each plot. Comparable samples of nine borings each were taken after seven cycles of the rotation in Section 1 and six cycles in Sections 2 and 3. The original samples were analysed at the same time as those taken at the end of the experiment. Procedures given in "Chemical Methods of Soil Analysis" (1) were followed in the preparation of the samples, the determination of pH value, base exchange capacity, exchangeable calcium, magnesium and potassium, total nitrogen, organic matter and adsorbed and easily acid-soluble phosphorus. The pH value and phosphorus status of all samples was determined and, in addition, all samples from Section 2 were analysed for exchangeable cations, base exchange capacity, organic matter and total nitrogen.

Crop yields and the results of soil analyses were evaluated by statistical treatment of data.

RESULTS

Changes in Chemical Properties of Soil

Analytical results for soil samples collected from Section 2 before any treatments were applied and for comparable samples taken after six cycles of the rotation are presented in Table 2. Applications of dolomitic limestone made in 1944 and 1947 and totalling slightly less than 2 tons per acre, are reflected by the decrease in soil acidity and increase in exchangeable magnesium. There was a decrease in exchangeable calcium although the soil was 80 per cent base saturated in 1954 and only 67 per cent in 1936. During the 18-year period cation exchange capacity decreased significantly as did exchangeable potassium, organic matter content and total nitrogen. In plots where manure was applied the average decreases in organic matter and total nitrogen, expressed in terms of the 1936 values, were 14.4 and 22.2 per cent respectively. Comparable values for the check plots were 24.8 and 29.0 per cent. Section 1 which received a total of 4.5 tons per acre of dolomitic limestone from 1943 to 1955 had a mean pH value of 6.65 in 1956. The corresponding value in 1936 was 5.91. In Section 3, where no limestone was applied, mean pH values in 1936 and 1955 were 5.37 and 5.31 respectively.

TABLE 3.—EFFECT OF VARIOUS TREATMENTS ON ADSORBED AND EASILY ACID SOLUBLE PHOSPHORUS IN SOIL
(Mean values for 12 plots)

Identification	Treatment number	Adsorbed and easily acid-soluble phosphorus (P)		
		Initial	Final	Difference
		p.p.m.	p.p.m.	p.m.p.
Levels of phosphorus				
2-0-6 at 750 lb./ac.	5	53	36	−17
2-4-6 " "	6	52	41	−11
2-8-6 " "	7	52	42	−10
2-10-6 " "	8	53	49	− 4
2-12-6 " "	2	52	49	− 3
Rates of application				
2-12-6 at 500 lb./ac.	13	49	43	− 6
2-12-6 " 750 "	2	52	49	− 3
2-12-6 " 1000 "	14	55	57	+ 2
2-12-6 " 1500 "	15	51	74	+23
Other treatments				
Manure at 10 tons/ac.	16	52	39	−13
" " 20 "	17	57	52	− 5
" " 10 " }	18	51	50	− 1
2-12-6 " 500 lb./ac. }				
Manure at 10 tons/ac. }	19	59	54	− 5
Superphosphate at 300 lb./ac. }				
No treatment				
Check	20	52	32	−20
L.S.D. P.05				6
L.S.D. P.01				8

The effect, on the phosphorus status of soil, of the continued application of various commercial fertilizers and of manure is shown for all sections in Table 3. At the beginning of the experiment the adsorbed and easily acid-soluble phosphorus content of the plots was relatively uniform. The mean values for 14 groups of 12 plots each ranged from 49 to 59 p.p.m. At the end of the experiment the range was 32 to 74 p.p.m. In terms of the initial values decreases in adsorbed and easily acid-soluble phosphorus in plots receiving no treatment, a 2-0-6 fertilizer at 750 pounds per acre, or manure at 10 tons per acre, were 38.5, 32 and 25 per cent respectively. In plots where 1500 pounds per acre of a 2-12-6 fertilizer were applied there was an increase of 45 per cent. While the change with a number of treatments was small the magnitude of increase or decrease was generally proportional to the amount of phosphorus applied.

The effect of repeated applications of various commercial fertilizers and of manure on the exchangeable potassium in soil is shown in Table 4. Irrespective of the treatment applied the level of exchangeable potassium declined during the experiment although in the majority of cases the magnitude of decline was practically identical. The levels of exchangeable potassium found at the end of the experiment indicate, however, that treatments applied influenced the final values. In those treatments involving different levels of potassium the higher the level applied, the higher the final value for exchangeable potassium. With one exception the same

TABLE 4.—EFFECT OF VARIOUS TREATMENTS ON EXCHANGEABLE POTASSIUM IN SOIL
(Mean values for 4 plots)

Identification	Treatment number	Exchangeable Potassium(K)		
		Initial	Final	Difference
		m.e./100 g.		
Levels of potassium				
2-12-0 at 750 lb./ac.	9	0.26	0.20	−0.06
2-12-3 " "	10	0.35	0.21	−0.14
2-12-6 " "	2	0.28	0.24	−0.04
2-12-9 " "	11	0.31	0.26	−0.05
Rates of application				
2-12-6 at 500 lb./ac.	13	0.27	0.23	−0.04
2-12-6 " 750 "	2	0.28	0.24	−0.04
2-12-6 " 1000 "	14	0.30	0.26	−0.04
2-12-6 " 1500 "	15	0.31	0.22	−0.09
Other treatments				
Manure at 10 tons/ac.	16	0.27	0.22	−0.05
" " 20 "	17	0.29	0.26	−0.03
" " 10 " }	18	0.28	0.24	−0.04
2-12-6 at 500 lb./ac. }				
No treatment				
Check	20	0.29	0.25	−0.04
L.S.D.				N.S.

definite trend was evident with respect to rates of application of 2-12-6 fertilizer and of manure.

Crop Yields

The average yields of swedes, oats and hay from 1936 to 1957 are presented in Table 5.

Irrespective of the treatment applied differences between swede yields on treated plots and on the untreated checks were highly significant and, in the majority of cases, yields on treated plots were approximately double those on the checks. In the treated plots the lowest yield occurred with a 2-0-6 fertilizer at 750 pounds per acre and the highest with a 2-12-6 fertilizer at 1500 pounds per acre. While yields with a number of treatments were not significantly different the data indicate that phosphorus level had a greater influence on yield than nitrogen or potassium level.

Although the majority of the treatments gave oat yields which were significantly greater than those produced on the untreated checks differences due to level of nitrogen or potassium were not significant. There were, however, significant differences due to level of phosphorus and rate of application of 2-12-6 fertilizer. The highest yield was obtained with manure at 20 tons per acre and differences between this yield and any other were significant or highly significant.

The effect of the various treatments on hay yields was rather similar to the effect on oat yields. Differences due to level of nitrogen, phosphorus or potassium were not significant. The highest yield occurred with 20 tons per acre of manure and with the exception of plots receiving 10 tons of manure plus 2-12-6 at 500 pounds per acre it was significantly higher than that obtained with any other treatment.

TABLE 5.—AVERAGE YIELDS, ALL SECTIONS, OF SWEDES, OATS AND HAY FROM 1936 TO 1957

Treatment number	Treatment	Application rates	Swedes (D.M.)	Oats	Hay (D.M.)
		lb./ac.	tons/ac.	bu./ac.	tons/ac.
Nitrogen levels					
1	0-12-6	750	1.96	39.8	1.44
2	2-12-6	750	2.04	42.9	1.41
3	4-12-6	750	2.18	40.8	1.40
4	6-12-6	750	2.20	40.9	1.42
Phosphorus levels					
5	2-0-6	750	1.41	37.9	1.31
6	2-4-6	750	1.88	40.0	1.42
7	2-8-6	750	2.01	40.0	1.41
8	2-10-6	750	1.94	37.2	1.34
2	2-12-6	750	2.04	42.9	1.41
Potassium levels					
9	2-12-0	750	1.77	41.6	1.30
10	2-12-3	750	1.98	40.3	1.35
2	2-12-6	750	2.04	42.9	1.41
11	2-12-9	750	2.07	42.9	1.39
Application rates					
13	2-12-6	500	1.87	38.7	1.29
2	2-12-6	750	2.04	42.9	1.41
14	2-12-6	1000	2.22	41.9	1.44
15	2-12-6	1500	2.31	44.8	1.50
Manure and combination treatments					
16	Manure	20000	1.77	41.8	1.52
17	"	40000	2.09	50.0	1.73
18	" + 2-12-6	20000) 500)	2.19	44.6	1.62
19	Manure + Superphosphate	20000) 300)	2.07	44.3	1.58
12	2-12-6 + Borax	750) 10)	2.10	42.3	1.41
20	Check		1.09	37.1	1.23
	L.S.D. P.05		0.14	4.1	0.14
	L.S.D. P.01		0.18	5.4	0.20

Swede, oat and hay yields with treatments involving minimum and maximum levels of nitrogen, phosphorus and potassium as well as rates of 2-12-6 fertilizer and of manure are given by rotation cycles in Tables 6, 7 and 8 respectively. The yields for each cycle are averages of those obtained in 3-year periods during which each crop occurred once on each section.

The variation in yields with rotation cycles, although greater for swedes than for oats or hay, suggests the influence of seasonal conditions. However, in spite of this variation the treatment effects with swedes were consistent and pronounced in each of the rotation cycles. In the case of oats and hay the effects, although relatively consistent, were slight or negligible in the majority of cases. The data for these two crops also

TABLE 6.—YIELD TRENDS FOR SWEDES AS SHOWN BY YIELDS WITH CERTAIN TREATMENTS DURING SIX ROTATION CYCLES

Treatment number	Treatment	Application rate	Rotation cycles					
			1	2	3	4	5	6
		lb./ac.	D.M. tons/ac.					
Nitrogen levels								
1	0-12-6	750	1.19	1.73	2.55	1.76	1.61	1.69
4	6-12-6	750	1.46	2.00	2.83	2.22	1.80	1.95
Phosphorus levels								
5	2-0-6	750	0.97	1.34	2.02	1.50	1.15	0.95
2	2-12-6	750	1.23	1.74	2.54	1.96	1.72	1.78
Potassium levels								
9	2-12-0	750	1.14	1.55	2.49	1.53	1.50	1.50
11	2-12-9	750	1.23	1.82	2.78	1.87	1.71	1.86
Application rates								
13	2-12-6	500	1.11	1.71	2.32	1.82	1.55	1.66
15	2-12-6	1500	1.36	1.90	2.82	2.32	1.89	2.08
16	Manure	20000	1.13	1.58	2.43	1.81	1.43	1.33
17	"	40000	1.20	1.81	2.63	2.23	1.92	1.86
No treatment								
20	Check		0.99	0.99	1.77	1.04	0.90	0.55

TABLE 7.—YIELD TRENDS FOR OATS AS SHOWN BY YIELDS WITH CERTAIN TREATMENTS DURING SIX ROTATION CYCLES

Treatment number	Treatment	Application rate	Rotation cycles					
			1	2	3	4	5	6
		lb./ac.	bu./ac.					
Nitrogen levels								
1	0-12-6	750	43.0	44.2	38.2	37.9	41.5	37.3
4	6-12-6	750	42.1	47.2	40.1	39.2	42.2	36.1
Phosphorus levels								
5	2-0-6	750	44.7	44.6	35.5	36.5	38.1	34.1
2	2-12-6	750	44.2	46.5	43.9	42.9	45.0	38.3
Potassium levels								
9	2-12-0	750	43.5	44.6	39.6	42.6	45.7	36.7
11	2-12-9	750	45.5	46.2	41.1	40.4	45.3	41.2
Application rates								
13	2-12-6	500	43.0	48.3	37.8	37.9	37.3	35.7
15	2-12-6	1500	45.0	48.0	42.1	42.6	49.7	43.6
16	Manure	20000	43.0	48.0	38.9	42.2	42.9	38.6
17	"	40000	48.8	50.5	47.5	54.7	57.3	46.6
No treatment								
20	Check		42.4	41.4	34.5	35.6	38.6	35.9

indicate that with most of the treatments yields showed some tendency to decline as the experiment progressed. There was little evidence of this tendency with the swede crop.

DISCUSSION

Soil analytical data show that where manure at 10 tons per acre, either alone or in combination with commercial fertilizers, was applied once in 3 years the original levels of organic matter and total nitrogen were not

TABLE 8.—YIELD TRENDS FOR HAY AS SHOWN BY YIELDS WITH CERTAIN TREATMENTS DURING SIX ROTATION CYCLES

Treatment number	Treatment	Application rate	Rotation cycles					
			1	2	3	4	5	6
		lb./ac.	tons/ac.					
Nitrogen levels								
1	0-12-6	750	1.66	1.52	1.59	1.22	1.32	1.33
4	6-12-6	750	1.68	1.66	1.47	1.21	1.22	1.41
Phosphorus levels								
5	2-0-6	750	1.60	1.44	1.37	1.08	1.20	1.22
2	2-12-6	750	1.68	1.50	1.46	1.11	1.30	1.43
Potassium levels								
9	2-12-0	750	1.58	1.50	1.27	1.01	1.11	1.34
11	2-12-9	750	1.61	1.56	1.52	1.13	1.19	1.33
Application rates								
13	2-12-6	500	1.55	1.35	1.31	1.11	1.14	1.32
15	2-12-6	1500	1.81	1.58	1.49	1.30	1.41	1.36
16	Manure	20000	1.61	1.49	1.68	1.36	1.48	1.53
17	"	40000	1.83	1.77	1.87	1.68	1.54	1.82
No treatment								
20	Check		1.31	1.53	1.47	1.12	1.11	1.36

maintained. A similar situation was found where manure alone was used at the rate of 20 tons per acre. The data also show that exchangeable potassium decreased during the course of the experiment, irrespective of the treatment applied. At the end of the experiment, however, the potassium status of various plots indicated a definite relationship between the amount of potassium applied and the exchangeable potassium content of the soil.

Changes in the phosphorus status of the soil, as shown by content of adsorbed and easily acid-soluble phosphorus, while not significant with some treatments, were pronounced with others. The latter included untreated plots, those receiving a 2-0-6 fertilizer at 750 pounds per acre, and plots where a 2-12-6 fertilizer was applied at 1500 pounds per acre. The analytical results suggest that in this experiment there was little change in the phosphorus status of the soil where approximately 100 pounds of P_2O_5, 10 tons of manure plus 60 pounds of P_2O_5, or 20 tons of manure per acre were applied once every 3 years. Where 180 pounds per acre of P_2O_5 was applied for each cycle of the rotation there was a highly significant increase in adsorbed and easily acid-soluble phosphorus.

Under the conditions of this experiment a number of treatments influencing swede yields had no apparent effect on the succeeding oat and hay crops. This is perhaps not surprising since all treatments were applied the year swedes occurred in the rotation. Thus the results suggest that residual effect of some treatments was negligible and that, even in short-term rotations, fertility applied for a hoed crop may be of little or no benefit to succeeding cereal and hay crops. This, however, was not the case with the manure treatments which apparently had a marked residual effect. Yield data also show the necessity of adequate soil phosphorus levels which, under the conditions of this experiment, were indicated to be of greater importance than either nitrogen or potassium levels.

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THE SIGNIFICANCE OF LOCAL SOIL TYPES TO SOIL FERTILITY STUDIES[1]

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ABSTRACT

Soil productivity data included in this study were obtained from field experiments laid down in areas of soil, characteristic of individual member profiles of catenary groups of the Weyburn and Oxbow Associations, and of a mapping complex comprising members of the Sceptre, Kindersley, and Flaxcombe Associations.

The criteria used to assess soil productivity included the yield of grain with and without phosphorus and nitrogen fertilization, uptake of fertilizer phosphorus, 'A' values (from field and greenhouse experiments) and extractable phosphorus ($NaHCO_3$ and H_2CO_3).

The data illustrate the variability in yield and response to phosphorus fertilization that can be expected within relatively short distances in any one field in which complexity of soil pattern occurs. These differences in productivity were closely associated with pedogenic differences used to classify the soils.

It was concluded that considerable care must be taken in the interpretation and application of fertility data obtained from small plot experiments as the data are applicable to only one particular soil type, in most instances the soil member on which the test was established; such data cannot be used to represent mapping units which include even closely associated soil types.

INTRODUCTION

The primary function of a soil survey program is to recognize and if possible group together soils of similar genesis, morphology, and associated physical and chemical characteristics. It is generally assumed that soils exhibiting differences in these characteristics will probably differ in productivity. The validity of this hypothesis is supported by a wealth of observations, but only by very limited experimental data. Many attempts have been made to relate productivity to soil type; not the least amongst these are those reported by Odell and Smith (7), Simonson and Englehorn (13), Odell (5, 6), Rust and Odell (11), and Shrader *et al.* (12).

Accurate appraisal of the effects of soil variations on crop production is a most difficult problem. Rust and Odell (11) suggest that some 30 plot locations on each soil type, with the yield tests repeated for a number of years to overcome climatic variations, are necessary to arrive at a reasonable productivity rating for any one soil.

The local complexity of soil pattern associated with glacial land forms which occur over much of the agricultural area of Saskatchewan has been discussed at length by Moss (3); this complexity makes most difficult the classifying and grouping of soil types into practical mapping units for purposes of recommendation and study. The same difficulties are encountered in the study of productivity and fertility levels of soil types in Saskatchewan. In most instances complexes of various soil types will be cultivated and cropped as single field units.

The initial attempts to relate soil type differences to crop yield differences reported in this study were not designed to arrive at typical (long-time) productivity ratings for each individual unit, but rather represent

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studies designed to compare the productivity and phosphorus fertility level of differing soil units (with the same management history) in any one year. The individual soil units chosen for study were those comprising single soil members of various catenas or catena complexes and occurring in single field units where cultural practices could be assumed to have affected all soil members similarly.

The term "soil members" as used here has been defined by Moss (3) as "principal genetic profiles" which have developed on a particular parent material within a certain soil zone. The pattern and distribution of these member profiles in relationship to the local catenary group suggest that they have developed as a result of variations in slope, aspect, drainage and vegetation.

EXPERIMENTAL PROCEDURE

Data included in this study were obtained from field experiments laid down on areas of soils characteristics of individual member profiles of catenary groups of the Weyburn and Oxbow Associations, and of a mapping complex comprising members of the Sceptre, Kindersley, and Flaxcombe Associations. Further descriptions of the Weyburn and Oxbow soils can be found in Soil Survey Report No. 12 (2); the mapping complex including the Kindersley, Flaxcombe and Sceptre soils has been described by Moss (4).

In each catenary study small randomized block experiments, including three fertilizer treatments and a check, with six replicates, were laid down on selected soil members occurring in one field. Since these fields had been worked as a unit, the past cultural practices could be assumed to have affected all soil members similarly. Any differences in yield and response to fertilizer could, therefore, be attributed to variations in soil characteristics, and associated micro-climate of the differing soil members. All field sites had been summerfallowed for one year prior to seeding.

The radioactive mono-ammonium phosphate used in these studies was supplied by the U.S. Bureau of Plant Industry, Beltsville, Maryland. The plots were seeded with a six-furrow, double-disk, V-belt rodrow seeder mounted on a Bolens Ride Master tractor. Each treatment consisted of three rows, the centre row being taken for yield determinations. Thatcher wheat seeded at a rate of 2 bushels per acre was used as the test crop.

Radioactive phosphorus and total phosphorus analyses were carried out as described previously (10).

DESCRIPTION OF SOILS

The member profiles and soil catena sites studied in these field experiments are described in accordance with the classification and latest numerical and descriptive terminology used by the National Soil Survey Committee for Canada, 1960*. They are all classified and named as Sub-Group, (IV) Profiles. The terminology previously used in classifying the soils of Saskatchewan, as reported by Moss (3), is also indicated in brackets.

*Report of the National Soil Survey Committee, 1960. Processed by the Soil Research Institute, Ottawa, Ont.

Oxbow Site

The Oxbow catena is described as a group of series or member profiles, found within the Black Soil Zone, consisting mainly of Chernozeinic Black and associated Solonetzic, Regosolic and Gleysolic profiles occurring on medium textured, moderately calcareous, and moderately stony glacial till. The soils are dominantly loams but range from sandy loam to clay loam in texture.

The site selected was located in an area of approximately 10 acres within the NE-32-19-18-W-2, about 6 miles north of the village of Zehner, Saskatchewan. The land form was roughly undulating, consisting of an irregular pattern of excessively-drained knolls, well-drained slopes and imperfectly-drained bottom lands, with dominant slopes between 2 and 5 per cent, and a frequency of undulation of over 3 per ½ mile. The vegetation of the area is typical of the parkland prairie or Aspen grove area (2).

Four member profiles were selected for study in the area, and are described as follows:

1. *Calcareous Black 1.32* (*columnar calcareous Black*). A moderately well-developed profile with some free carbonates in the colour B horizon; occurring on the well- to excessively-drained upper slope position in the catena.
2. *Orthic Black 1.33* (*columnar prismatic Black*). A well-developed profile with a dark brown prismatic structure; carbonate free B; occurring on the well-drained intermediate slope position.
3. *Orthic Dark Grey 1.43* (*slightly degraded Black*). A well-developed profile with a dark grey brown Aa horizon with a cloddy platy structure; underlain by a textural B characterized by prismatic breaking to irregular blocky structure; occurring in the moderately well-drained lower intermediate slope position and presumably developed under an Aspen tree cover.
4. *Low Humic Eluviated Gleysol 6.42* (*depression grey podzolic*). A well-developed profile with a light brownish grey platy structured Aa horizon; underlain by a textural, very dark grey mottled gleyed B horizon; occurring in the imperfectly-drained lowest position in the catena site, and presumably developed under tree and meadow vegetation.

Weyburn Site

The Weyburn catena is described as a group of series or member profiles, occurring within the Dark Brown Soil Zone, consisting mainly of chernozemic Dark Brown, and associated Solonetzic profiles occurring on medium textured, moderately calcareous and moderately stony glacial till. The soils are dominantly loam but vary from sandy loam to clay loam in texture.

The soils selected for study were situated along a half-mile strip in the SW-35-36-2-W-3, about 20 miles east of Saskatoon. The land form was a gently to moderately rolling morainic type, consisting of an irregular pattern of excessively-drained knolls and upper slopes, well-drained intermediate and lower slopes (5-9 per cent) and imperfectly-drained depressions and bottom lands. The vegetation of the area is typically mixed prairie.

The eight member profile sites selected for study are described below:

1. *Calcareous Dark Brown 1.22* (*columnar calcareous*). A thin profile with a weak development of a colour B horizon and the C horizon occurring at 12-inch depth; free carbonates present in all horizons; occurring on a well-drained upper slope position.
2. *Truncated Calcareous Dark Brown 1.12* (*Truncated columnar calcareous*). A very thin profile with the C horizon occurring at 9-inch depth; solum strongly

calcareous throughout; occurring on a knoll position which has suffered from severe surface erosion.

3. *Orthic Dark Brown 1.23 (columnar prismatic dark brown).* A profile with much of the original A horizon lost due to wind erosion; occurring on an intermediate slope position.
4. *Orthic Dark Brown 1.23 (columnar prismatic dark brown).* A well-developed profile in a lower moderately well-drained slope position; gypsum in the lower B above the Ca horizon suggests the upward movement of salts.
5. *Imperfectly drained Rego Dark Brown 1.21/6 (imperfectly drained granular calcareous Dark Brown).* A profile developed on roughly sorted glacial till; occurring in an imperfectly-drained lower slope position; free carbonates throughout the profile. The Ah horizon is thick and extends below the Aa layer.
6. *Orthic Dark Brown 1.23 (columnar prismatic Dark Brown).* A profile characterized by a very thin carbonate free B; occurring on an upper slope position.
7. *Orthic Dark Brown 1.23 (columnar prismatic Dark Brown).* A profile with a well-developed carbonate free B horizon; occurring on a well-drained intermediate slope position.
8. *Eluviated Dark Brown 1.24 (depression solodic).* A profile characterized by a platy structured Ae horizon below the Aa, a thick carbonate free prismatic B extending to a depth of 24 inches; occurring in an upland depressional position with moderately free internal drainage.

Kindersley Sites

Two sites were selected for study in the Kindersley area of western Saskatchewan to represent a local mapping complex of parent materials and catenary profiles occurring in the Brown Soil Zone on an area of variable lacustrine clay deposits overlying a slightly saline glacial till. Within this complex, the profiles developed on uniform heavy clay deposits were correlated with the Sceptre Association, the lighter textured variable clay deposits with the Kindersley association, and the thin clay deposits over glacial till were described as shallow Kindersley soils. Profiles developed solely on the glacial till were classified as members of the Flaxcombe association (4). Soil profiles in the Sceptre association were mainly weakly developed Rego-chernozemic types whereas the profiles of the Kindersley and Flaxcombe soils were dominantly solonetzic. The pattern of occurrence of these soils was largely dependent on the topographic factors of slope and relief. The Sceptre soils usually occupied the lower positions of most uniform lacustrine deposition, the Kindersley the shallow marginal lake positions whereas the shallow Kindersley and Flaxcombe soils occupied knolls and higher slope positions within the area.

The following n.ember profiles were selected for study:

1. *Rego Brown 1.11 (cloddy-gramular) member of the Sceptre association.* A heavy clay profile with a weakly developed brown A horizon; cloddy to fine granular structure and usually containing some free lime carbonate. The A horizon grades into an olive brown, calcareous C horizon.
2. *Imperfectly-drained Mull Regosol 5.12/5 (massive, poorly drained) member of the Sceptre association.* A heavy clay profile with a thin greyish brown to bluish grey Aa horizon having a hard, coarse granular structure when dry; underlain by a compact massive structured grey B/C horizon with rusty coloured mottles. The profile is frequently lime carbonate free, and occurs in depressional or flat areas subject to periodic flooding.
3. *Brown Solonetz 2.11 (solonetz brown) member of the Kindersley association.* This soil is characterized by a greyish brown, cloddy-platy Aa horizon of clay texture; a heavier textured, carbonate free, brown solonetzic B horizon with a prismatic structure breaking to very hard sub-angular fragments. The C horizon is a calcareous, slightly saline, lacustrine clay.

4. *Brown Solonetz 2.11 (solonetz brown) member of the Shallow Kindersley association.* The profile is characterized by a greyish brown, cloddy structured clay loam Aa horizon; a clay textured, prismatic solonetzic B; a glacial till, clay loam D horizon. Some stones occur in the lower B and D horizons.
5. *Brown Solonetz 2.11 (solonetz brown) member of the Flaxcombe association.* The profile is characterized by a greyish brown, hard cloddy sandy clay loam Aa horizon; a compact, solonetzic structured, clayey B horizon; a light brownish grey, moderately compact, slightly saline, clay loam glacial till, C horizon.

The site for the first study of this catena complex in 1956 was located on the NW-15-29-23-W-3. The four member profiles selected included a Rego Brown (cloddy granular) member of the Sceptre soil and three brown solonetzic members of the Kindersley, Shallow Kindersley and Flaxcombe associations respectively.

TABLE 1.—COMPARATIVE DATA OBTAINED WITHIN ONE FIELD ON FOUR MEMBER PROFILES OF THE OXBOW CATENA

Soil Member	Check	Fertilizer treatment, lb. P_2O_5/ac. ($NH_4H_2PO_4$ used as P source)			
		20	40	20 plus 20 lb. N as NH_4NO_3	L.S.D. (P=.05)
(A) *Yield of grain, bu./ac.*					
Calcareous Black	15.9	21.4	24.8	23.0	1.9
Orthic Black	30.8	42.9	45.4	42.8	5.8
Orthic Dark Grey	17.7	31.5	32.5	28.7	4.6
Low Humic Eluviated Gleysol	10.3	16.0	15.2	13.6	3.4
L.S.D. (P=.05)	2.2	2.6	5.0	3.4	
(B) *Milligram percentage phosphorus in the grain*					
Calcareous Black	382	373	380	375	N.S.
Orthic Black	372	371	359	361	N.S.
Orthic Dark Grey	356	381	371	367	N.S.
Low Humic Eluviated Gleysol	451	443	433	440	N.S.
L.S.D. (P=.05)	24.8	22.5	18.9	22.7	
(C) *Percentage utilization of applied phosphate*					
Calcareous Black		15.2	12.6	17.0	1.2
Orthic Black		29.2	24.8	32.4	1.7
Orthic Dark Grey		31.0	23.4	33.0	1.6
Low Humic Eluviated Gleysol		14.9	10.4	13.7	1.0
L.S.D. (P=.05)		4.1	3.5	3.8	
(D) *Fertilizer phosphorus as a percentage of total phosphorus in the grain*					
Calcareous Black		27.6	39.8	28.4	1.0
Orthic Black		27.7	43.1	30.8	2.1
Orthic Dark Grey		39.1	55.1	45.3	2.6
Low Humic Eluviated Gleysol		30.9	45.1	33.9	1.8
L.S.D. (P=.05)		4.3	4.0	4.8	

	(E) *Available soil phosphorus, lb. P/ac.*			
	Field 'A' value	Greenhouse 'A' value	Extract phosphorus	
			H_2CO_3	$NaHCO_3$
Calcareous Black	24.9	27.5	46.4	15.6
Orthic Black	23.6	48.0	58.0	35.2
Orthic Dark Grey	14.0	28.0	24.2	17.2
Low Humic Eluviated Gleysol	20.9	51.0	42.0	38.0
L.S.D. (P=.05)	3.3	3.0		

In 1957 a second study was made on the NW-19-29-23-W-3. At this site, a complex of two member profiles of the Sceptre soil, a well-drained Rego Brown (cloddy-granular) and imperfectly-drained Mull Regosol (massive) were studied, together with two brown solonetzic members of the Kindersley and Flaxcombe associations.

RESULTS AND DISCUSSION

Criteria used to assess the comparative productivity and phosphorus fertility level of the various member profiles of any one catenary group included yields of grain with or without fertilization, percentage total-P, uptake of applied fertilizer-P, and the ratio of fertilizer-P to total P in the grain. In addition, 'A' values determined from field and greenhouse experiments, together with chemical soil extractants were employed as quantitative indicators of the available phosphorus content in the soil.

Oxbow Site

Yield comparisons between the four members of the Oxbow catena are given in Table 1(A). The marked and, in each instance, significant differences between the check yields of the different members were, in general, increased in magnitude with the use of $NH_4H_2PO_4$. Only in one instance, on the Calcareous Black profile, was there an increase in yield with application of additional nitrogen, but this increase was not significant. The low yields recorded for the Low Humic Eluviated Gleysol member can, in part, be attributed to the poor tilth of the Aa horizon; the soft loose condition of the surface soil favoured a rapid loss of surface moisture immediately after seeding, thus resulting in erratic germination. In addition, the tendency of the Aa to form a hard surface crust following late June rains undoubtedly retarded growth and stooling of the grain.

The percentage yield increase, based on the average yield increase over the check from both the 20- and 40-pound P_2O_5 treatments, can be used as an indication of the phosphorus fertility level of the four members. Thus, the percentage increase for the Calcareous Black, Orthic Black and Low Humic Eluviated Gleysol (45, 43 and 51 per cent respectively) were similar, but were considerably less than the 81 per cent increase recorded for the Orthic Dark Grey member.

As is indicated in Table 1(B), the percentage phosphorus in the grain was statistically identical for the three well-drained soil members and, in comparison, considerably higher for the grain grown on the Low Humic Eluviated Gleysol member. This difference in phosphorus content of the grain grown on these closely associated soils is equally as large as those reported for grain grown under widely differing soil and climatic conditions in Saskatchewan (8). It was concluded from these earlier studies that variations in percentage phosphorus do not necessarily reflect the phosphorus fertility level of the soil but, rather, are influenced by the level of available nitrogen in addition to other soil and environmental factors.

The percentage uptake of applied phosphorus [Table 1(C)], while in part reflecting total yield, is also influenced by the level of available soil phosphorus. Previous studies (11) have shown that wheat grown on soils high in available phosphorus will utilize less fertilizer phosphorus than when

grown on phosphorus-deficient soils. These data show that the percentage utilization of the applied fertilizer varied greatly between certain soil members, the uptake of phosphorus by grain grown on the Orthic Dark Grey and Orthic Black soils being similar, and almost twice that recorded for the other two members. It is of interest to note that the wheat utilized more of the fertilizer phosphorus when an additional 20 pounds per acre of N were applied together with the phosphorus than from the $NH_4H_2PO_4$ 20 pounds P_2O_5 treatment. This can be attributed to the influence of the increased ammonium ion content from the NH_4NO_3 used as a nitrogen source (10).

A further criteria used to assess the comparative productivity of the four Oxbow members, the percentage fertilizer phosphorus in the grain, is given in Table 1(D). Ordinarily, 20 to 30 per cent of the phosphorus in the grain may be derived from the fertilizer (20-pound P_2O_5 rate of application) but under drought conditions this value may increase to approximately 80 per cent (1). Other factors, such as the pattern and extent of root development and available soil phosphorus in both surface and subsoil, can also be expected to materially alter the percentage plant phosphorus derived from the fertilizer. Thus, the high value recorded for the Orthic Dark Grey member, in comparison to the other three members, in addition to reflecting a soil more deficient in phosphorus [see Table 1(E)] may also be indicative of a changed soil environment affecting the root distribution pattern.

TABLE 2.—COMPARATIVE DATA OBTAINED ON MEMBER PROFILES OF THE WEYBURN CATENA

Soil member	Yield check	Bu./ac. fert.*	*% Util. fert.-P	Mg.%P grain (check)	*Fert.-P as % total-P (grain)	Avail. Soil-P lb.P/ac.	
						'A' val.	CO_2 ext.
Calcareous Dark Brown	39.6	44.3	3.7	405	6.5	144	255
Calcareous Dark Brown (eroded truncated)	30.0	35.9	8.3	433	15.8	71	22
Orthic Dark Brown (eroded)	20.6	27.2	12.3	427	45.2	28	14
Orthic Dark Brown	36.6	42.7	13.8	367	29.5	31	13
Imperfectly-Drained Rego Dark Brown	39.6	49.7	13.2	328	21.7	47	15
Thin Orthic Dark Brown (shallow knoll)	28.1	35.7	11.7	426	25.3	39	21
Orthic Dark Brown	29.4	37.6	14.2	458	29.1	31	29
Eluviated Dark Brown	24.7	34.6	13.2	423	28.0	32	16
L.S.D. (P=.05)	3.8	3.9	1.3	57	3.3	13	—

*All fertilizer data represent the average of that obtained from 20 and 40 pounds P_2O_5/ac. of $NH_4H_2PO_4$.

Various indices of available soil phosphorus for each of the member profiles are tabulated in Table 1(E). Both field and greenhouse 'A' value measurements suggest that the marked differences in available soil phosphorus can, in part, explain the differences in crop yields obtained on the four related soil members. It should be noted that the different measurements place the soils in a somewhat different order of phosphorus fertility level. The 'A' values determined under controlled conditions in the greenhouse have been shown to be somewhat better indexes of available phosphorus levels than either field 'A' values or chemical extractants (9).

Weyburn Site

Although similar treatments to those given for the Oxbow catena plots were used on the eight member sites of the Weyburn catena, only portions of these data are included in Table 2. The yield data presented for each soil member illustrate the marked differences, not only in check yields, but also in yield increases resulting from $NH_4H_2PO_4$ fertilization, between the various members. These yield differences are complemented by equally marked differences in utilization of fertilizer phosphorus, in the proportion of fertilizer phosphorus to total phosphorus, and in the percentage phosphorus in the grain. The differences in response to the applied phosphorus fertilizer can be partially explained on the basis of the 'A' value data, as a significant negative 'r' value of 0.664 suggests at least a partial dependence of the recorded yield increases on available soil phosphorus.

Kindersley Site

Two individual studies were conducted on this catena complex, the first during the 1956 growing season, and the second the following year. A partial list of the data collected from this 2-year study is presented in Table 3. As has been observed previously from the Oxbow and Weyburn studies, it is readily evident that the soil members of this complex differ appreciably in productivity and phosphorus fertility level. Data are available from three members, the Sceptre Rego Brown, the Kindersley Brown Solonetz, and the Flaxcombe Brown Solonetz, for a 2-year period. (Abundant precipitation fell during the 1956 growing season, while there was little or no effective rainfall during the 1957 April-August period). Thus, it should be possible to determine the effect of climate on the comparative productivity of these members.

In 1956, the Rego Brown member, usually assumed to be the most productive of the three members, was characterized by a check yield considerably less than either Brown Solonetz member; the much greater response to phosphate fertilizer recorded on the cloddy granular Rego Brown plot than on the solonetzic members narrowed these differences appreciably. In contrast, the check yields obtained on the three plots in 1957 were statistically identical; comparisons of fertilized yields show the Rego Brown heavy clay 5.2 bushels above the Kindersley Brown Solonetz clay, and 13.2 bushels in excess of that obtained on the Flaxcombe Brown Solonetz sandy clay loam. It is to be noted, however, that, in making such comparisons between 2 years' data obtained from two different fields, the assumption must be made that past management practices have not in-

TABLE 3.—COMPARATIVE DATA OBTAINED ON MEMBER PROFILES OF THE KINDERSLEY MAPPING COMPLEX

Soil Member	Yield, bu./ac.		% Util. fert.-P	Mg. % P grain (check)	*Fert-P as % total -P	Available soil-P, ob. P/ac.			
	Check	Fert.*				*Field 'A' value	Greenhouse 'A' value	H_2CO_3 ext-P	$HaHCO_3$ ext-P
1956									
Sceptre Rego Brown (Cloddy granular)	29.7	51.3	20.5	269	32.1	27	17	20	11
Kindersley Brown Solonetz	51.9	57.0	22.7	288	29.4	31	25	39	37
Shallow Kindersley Brown Solonetz	45.3	56.7	17.6	313	21.8	46	42	62	58
Flaxcombe Brown Solonetz	46.0	65.0	21.0	276	26.6	37	28	54	41
L.S.D.	10.0	8.1	2.0	21	3.1	9	5	—	—
1957									
Sceptre Rego Brown (Cloddy granular)	30.6	46.1	17.2	301	28.0	35	18	18	8
Sceptre imperfectly-drained Mull Regosol	58.7	63.4	10.5	322	11.0	107	73	68	54
Kindersley Brown Solonetz	33.8	40.9	15.1	317	25.1	38	23	18	14
Flaxcombe Brown Solonetz	27.9	32.9	14.0	308	30.7	38	55	38	32
L.S.D.	6.9	6.0	1.7	9	3.6	7	4	—	—

*All fertilizer data represent the average of that obtained from the 20 and 40 pounds P_2O_5/ac. treatments of $NH_4H_2PO_4$.

fluenced the results. Such an assumption would be difficult to justify. However, it can be concluded that there is a strong possibility that climatic conditions may influence the comparative productivity of member profiles of any one catenary group of soils.

DISCUSSION AND SUMMARY

It was noted initially that an important hypothesis in soil classification is that crop yield differences may be associated with the pedogenic differences used to separate soils into differing units. In general, the criteria used to characterize the productivity and phosphorus fertility levels of the member profiles of the Oxbow, Weyburn and Kindersley complex justify the validity of the field separations.

While a long-term appraisal of the characteristic productivity level of each member would have considerable significance in an agronomic evaluation of soils, such an approach was not attempted in this study. Rather, it has been shown that the data illustrate the variability in yield and response to phosphorus fertilization that can be expected within relatively short distances in any field in which complexity of soil pattern occurs. To the soil scientist, and perhaps to the agronomist, it is of considerable significance that this variability can be related to individual soil units. Thus, it can be concluded that any productivity data (response to fertilizers, phosphorus yield curves, etc.) obtained from any one small plot experiment, cannot be considered as representative of the field, of the catenary group of soils, or of the soil association to which the particular soil unit in the plot area belongs; rather, the data are applicable only to the one particular soil unit, in most instances a soil member, on which the test was established. This conclusion has special significance particularly where recommendations, with respect to fertilizer usage by farmers, are made from the data, or where the data are to be used to characterize the productivity of any mapping unit comprising more than one soil member.

During the 1958 meetings of the National Soil Fertility Committee summary reports of practically all fertilizer tests that have been conducted on the diverse soils of Western Canada were presented. It was clearly evident that, in spite of the vast amount of fertility work that has been completed in the past, it was most difficult, and in many instances impossible, to relate these data to any pedogenic grouping of soils. The authors contend that this apparent inability to relate productivity to recognized soil mapping units could be due to the lack of recognition of the specific soil members on which these tests had been established.

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THE INFLUENCE OF FERTILIZER PLACEMENT AND RATE OF NITROGEN ON FERTILIZER PHOSPHORUS UTILIZATION BY OATS AS STUDIED USING A CENTRAL COMPOSITE DESIGN[1]

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ABSTRACT

A greenhouse study was conducted to determine the optimum fertilizer phosphorus placement for oats and to determine the influence of nitrogen rate on the absorption of fertilizer phosphorus. A central composite design in three variables was used to permit the development of quadratic equations to express the response criteria as functions of the placement variables — horizontal distance and depth from the seed — and rate of nitrogen.

The fertilizer phosphorus absorption was determined at four stages of growth, the last stage being 58 days after planting. The dry weight of tops, total phosphorus content and per cent of the phosphorus derived from the fertilizer were determined at the completion of the experiment 58 days after planting.

At the 14-day stage fertilizer phosphorus absorption was greatest from fertilizer placed with the seed but, at the 28- and 42-day stages, was greatest from fertilizer placed 1 inch to the side and 2 or 3 inches below the seed. At the 58-day stage, fertilizer placed with the seed resulted in the greatest absorption of fertilizer phosphorus. The influence of placement on the per cent of the plant phosphorus that was derived from the fertilizer was similar to that on fertilizer phosphorus absorption.

Nitrogen increased fertilizer phosphorus absorption at all but the 14-day stage, increased plant weight to a lesser extent and decreased the per cent phosphorus in the tops at the 58-day stage.

INTRODUCTION

The efficiency with which fertilizer is utilized by a crop is a major factor in determining the economic returns from fertilization. Extensive investigations have indicated that, in general, fertilizer at the side and below the seed is utilized more effectively by row crops than that with the seed. Fertilizer placement studies with cereal grains, however, have usually compared only a seed placement with a broadcast application. Because placement with the seed has generally proven superior, and there is little information on the effectiveness of various band applications, the fertilizer for cereal grains is generally applied with the seed. Although fertilizer placed with the seed tends to increase yield due to greater nutrient supply, it may decrease yield due to the injurious concentration of salts. As the rate of fertilization increases, the injurious effects will become greater than the beneficial ones and the yield will decrease. This may be, in part, responsible for the lack of response of the small grains to higher rates of fertilizer with the seed.

Olsen and Dreier (11) have reported reductions in stand and yield of wheat from applications of 10 pounds of nitrogen per acre with the seed. The greatest reductions occurred when moisture supply at seeding was low and no additional moisture was received following seeding to leach the salts away from the seeds. At higher rates, full germination did not occur at any moisture level unless a moisture increment was received shortly after seeding. Similar findings have been reported by Cook *et al.* (4). Thus,

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there is a possibility of yield reductions even with moderate rates of fertilizer applied with the seed. Broadcast applications do not appear to reduce stand (11). However the utilization of phosphorus from broadcast fertilizer is considerably lower than from fertilizer with the seed. Olsen and Dreier (11) reported that fertilizer mixed with the soil at potting time in greenhouse studies was, on the average of six experiments, only 60 per cent as effective for oats as when applied with the seed. Cook *et al.* (4) and Barber (1) have reported similar findings for wheat.

The injurious effect of fertilizer appears to occur only when the fertilizer is in contact with the germinating seed. A root can survive and indeed proliferate extensively in a fertilizer band where the salt concentration is such that it would prevent the seed from germinating (10). Thus, if a placement away from the seed supplied the plant with as much or more nutrient as one with the seed, much higher fertilizer rates could be used without injurious effects and might result in greater yield responses.

The objectives of the study reported herein were to determine for oats under greenhouse conditions: 1) the optimum fertilizer phosphorus placement, and 2) the influence of rate of nitrogen on the utilization of phosphorus from the various placements.

MATERIALS AND METHODS

Experimental Design and Statistical Analysis

The experimental design used was a central composite design in three variables as developed by Box (2) and applied to biological studies by Hader *et al.* (5). This design utilizes 15 selected factor combinations from a 5^3 factorial which permit the development of a polynomial relationship. This polynomial defines a response surface in four dimensions. The variables used in the experiment were horizontal distance from the seed (X_1), depth (X_2) and rate of nitrogen (X_3). For ease of analysis the levels of the three variables were coded to the values shown in Table 1. The corresponding values of each variable are also shown in the table. The three-dimensional configuration of the levels was identical to that shown by Hader *et al.* (5) for a composite design in three variables. The two-dimensional arrangement of the placement variables is shown in Figure 1. The levels of nitrogen applied with each placement are shown in brackets below the respective points. The seed was placed 1.25 inches below the

TABLE 1.—EXPERIMENTAL VALUES USED FOR HORIZONTAL DISTANCE AND DEPTH OF PLACEMENT AND RATE OF NITROGEN

Coded value	Actual Value		
	X_1 Horizontal distance from seed (in.)	X_2 Depth below seed (in.)	X_3 Rate of nitrogen (lb./ac.)
−2	0	−1*	0
−1	1	0	5
0	2	1	10
1	3	2	15
2	4	3	20

*1 inch above seed

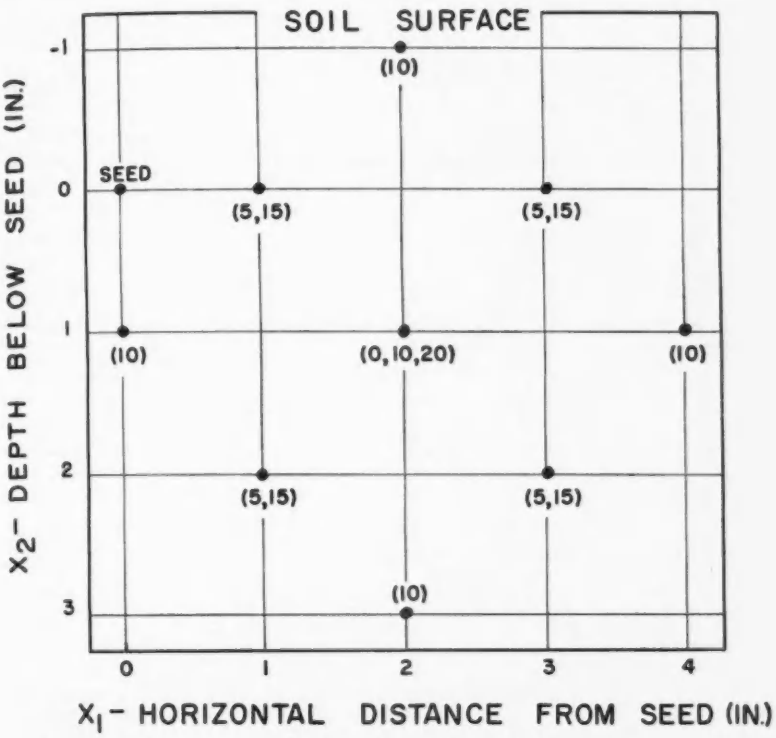

FIGURE 1. The two-dimensional configuration of fertilizer placement variables showing nitrogen rates (lb./ac.) in brackets at respective points.

soil surface which corresponded to a coded value of −1 for depth (X_2). Replication of the complete design resulted in the centre point in the design – coded values 0, 0, 0 – being replicated ten times and the 14 remaining points being duplicated. In addition, fertilizer was placed with the seed at the 0-, 10-, and 20-pound rates of nitrogen, six pots being included at each rate. Since the experimental design does not include this placement, the data from the placement with the seed were not used in the development of the regression equations because of extra mathematical complexity. However, the data were used for comparative purposes. The five pots of the central design point and the three pots of each treatment with the seed were randomized in each replicate as individual treatments. The analysis of variance breakdown is shown in Table 2. The mean square associated with the 22 degrees of freedom for remainder was used as the experimental error.

The data obtained were used to develop a quadratic equation of the form –

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3.$$

In this equation, Y is the response criteria and b_0 indicates the expected

TABLE 2. — ANALYSIS OF VARIANCE PLAN USED FOR ALL RESPONSE CRITERIA

Source of variation	d.f.	
Replication	1	
Treatment	14	
Linear regression component		3
Quadratic regression component		6
Lack of fit		5
Remainder	22	
Centre points		8
Replication x treatment		14
Total	37	

TABLE 3. — MATRIX OF X-VARIABLES AND SOLUTIONS FOR LEAST SQUARES EQUATIONS

Matrix of X-Variables										Y
X_0	X_1	X_2	X_3	X_1^2	X_2^2	X_3^2	X_1X_2	X_1X_3	X_2X_3	
1	−2	0	0	4	0	0	0	0	0	
1	−1	−1	−1	1	1	1	1	1	1	
1	−1	−1	1	1	1	1	1	−1	−1	
1	−1	1	−1	1	1	1	−1	1	−1	
1	−1	1	1	1	1	1	−1	−1	1	
1	0	−2	0	0	4	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	
1	0	0	0	0	0	0	0	0	0	
1	0	0	−2	0	0	4	0	0	0	
1	0	0	2	0	0	4	0	0	0	
1	0	2	0	0	4	0	0	0	0	
1	1	−1	−1	1	1	1	−1	−1	1	
1	1	−1	1	1	1	1	−1	1	−1	
1	1	1	−1	1	1	1	1	−1	−1	
1	1	1	1	1	1	1	1	1	1	
1	2	0	0	4	0	0	0	0	0	

$b_0 = 0.0945945\ (OY) - 0.0270270 \sum (iiY)$
$b_{ii} = -0.0270270\ (OY) + 0.0156250\ (iiY) + 0.0054899 \sum (iiY)$
$b_i = 0.0312500\ (iY)$
$b_{ij} = 0.0625000\ (ijY)$

response at the centre point with coded values 0,0,0. The linear coefficients — b_1, b_2, b_3 — indicate the slope of the surface at the centre point for the X_1, X_2, and X_3 variables, respectively. The quadratic components — b_{11}, b_{22}, b_{33} — indicate the degree of curvature of the surface in the respective directions, and the cross-product coefficients — b_{12}, b_{13}, b_{23} — indicate the interaction between the respective variables (5). The values of these coefficients were determined in the manner described by Hader *et al.* (5) and Cochran and Cox (3). Table 3 shows the matrix of X — variables used in developing the least squares equations. The solutions of the least squares equations shown in Table 3 were obtained by inversion of the matrix. The significance of the coefficients was tested by calculation of the ratio of each coefficient to its standard error as described by Cochran and Cox (3). This ratio follows Student's t distribution.

Experimental Procedure

Ten oat plants were grown in a straight line across a metal pot 10 inches square by 8 inches deep. Each pot was lined with a polyethylene bag and filled to a depth of 6 inches with soil. The soil used was from the Ac horizon of a Burford sandy loam with a dilute-acid-soluble plus adsorbed phosphorus content (12) of 150 pounds P_2O_5 per acre and a pH of 7.0. The soil was pulverized by passing through a "Royer"[1] previous to potting. P-32-labelled concentrated superphosphate[2] (45.6 per cent P_2O_5) was applied in bands parallel to the oat row at a rate of 40 pounds P_2O_5 per acre on a length-of-row basis. The nitrogen was applied in the band with the phosphorus as NH_4NO_3 on the same basis. A slotted wooden form was used to obtain the proper dimensional relationship between the fertilizer band and the seed row. Following seeding, the soil surface was covered with approximately 0.5 inches of white silica sand to reduce surface evaporation. Thus moisture tension within the pot was maintained uniform except as influenced by removal by the roots. Distilled water was then added to the pots to bring the soil to or near the moisture equivalent value. The pots were watered periodically thereafter by weighing and adding distilled water equivalent to that lost by transpiration. Attempts were made to keep the moisture content above 50 per cent of available moisture at all times but at later growth stages this was not always possible.

Experimental Determinations

The fertilizer phosphorus absorption was determined at three stages of growth using the in-situ technique described by Miller and Werkhoven (9). A fourth determination was made at the dough stage following harvesting using the briquet technique of MacKenzie and Dean (7) as modified by Miller and Ohlrogge (8).

[1]Distributed by Brown Engineering Corp., Toronto, Ont.
[2]Obtained from U.S.D.A. Plant Industry Station, Beltsville, Maryland.

TABLE 4.—COEFFICIENTS OF REGRESSION EQUATIONS EXPRESSING FERTILIZER PHOSPHORUS ABSORPTION BY OATS (MGM./POT) AT FOUR DATES AS A FUNCTION OF HORIZONTAL DISTANCE AND DEPTH OF PLACEMENT AND RATE OF NITROGEN

Coefficient	Time — Days after planting			
	14	28	42	58
b_0	0.3021**	2.3507**	3.0303**	7.4846**
b_1	−0.3587**	−0.3802**	−0.0893	−0.5334*
b_2	0.0378	0.3087**	0.2757**	−0.2484
b_3	0.0099	0.7634**	0.7188**	0.9903**
b_{11}	0.1178**	−0.1622*	−0.1424	−0.4302*
b_{22}	−0.0367	0.0509	−0.0003	−0.0277
b_{33}	−0.0103	−0.0189	0.0948	−0.0027
b_{12}	−0.0294	−0.0162	0.0218	0.3681
b_{13}	0.0404	0.1610	0.2549	−0.0544
b_{23}	0.0057	0.0616	0.2300	0.0681
R^2	0.825	0.815	0.743	0.517

*—Significant at .05 probability level
**—Significant at .01 probability level
R—Multiple correlation coefficient

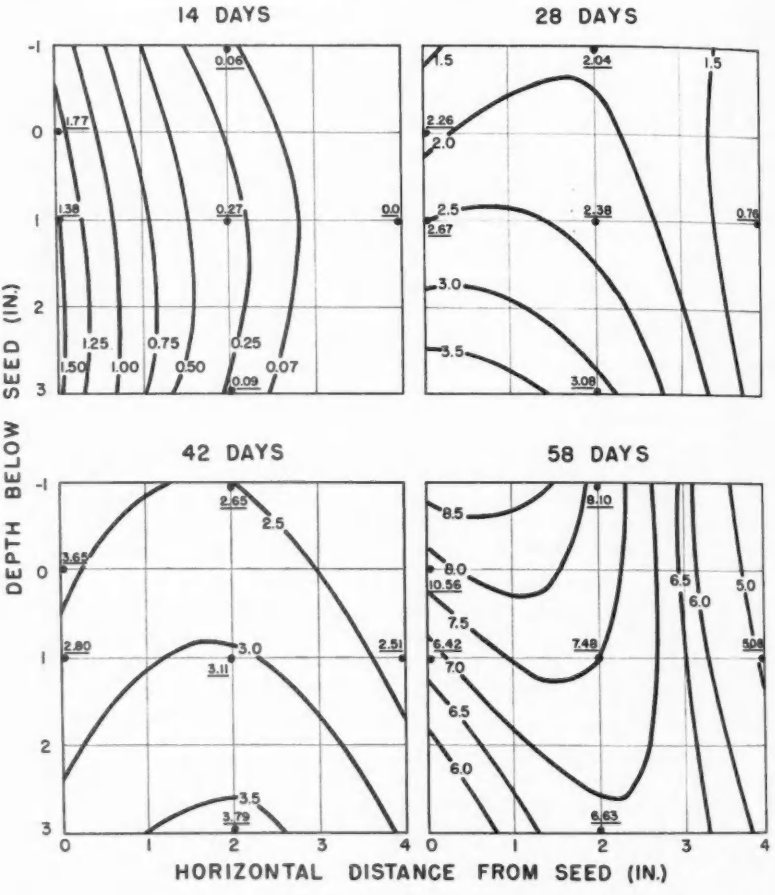

FIGURE 2. Contour lines showing placements that gave equal fertilizer phosphorus absorption by oats (mgm./pot) at four growth stages as calculated from the regression equations for the 10 lb./ac. nitrogen rate*.

*Underlined values are experimentally determined values at the respective points.

The weight of tops (grain plus straw) was determined following oven-drying at 70°C. for 48 hours. The total phosphorus content was determined using the molybdivanadophosphoric acid method (6) following dry ashing in a muffle furnace.

RESULTS AND DISCUSSION

Fertilizer Phosphorus Absorption

The coefficients of the regression equations expressing the fertilizer phosphorus content (mgm./pot) at each of the four stages as a function of horizontal distance, depth and rate of nitrogen are shown in Table 4. The

component or variance for lack of fit was non-significant for all dates. The equations allow an estimation to be made of the fertilizer phosphorus absorption from any placement within the tested region. To do this, the coded values must be used for the values of Xi in the prediction equation.

The data can also be represented by surfaces in three dimensions as calculated from the regression equations.

Since this is very difficult to show diagrammatically, the contour lines of equal fertilizer phosphorus absorption (mgm./pot) for one plane (10 pounds N/acre) are shown for each date in Figure 2. The underlined values in Figure 2 are the experimentally obtained values at the respective points.

Fourteen days after planting the linear coefficient b_1 was significantly different from zero and negative, indicating that at the central point of the design (2 inches to side, 1 inch below, 10 pounds N/acre) the absorption decreased as the horizontal distance increased. The quadratic coefficient, b_{11}, was also significant and positive, indicating that the fertilizer phosphorus absorption decreased most rapidly with the first increments of horizontal distance from the seed. At the remaining stages, the linear coefficient was still negative but the quadratic component changed from positive to negative indicating that the surface was curved in the opposite direction. As can be seen from Figure 2, the fertilizer phosphorus absorption increased as the horizontal distance from the seed increased from 0 to 1 inch and then decreased with increasing distance. Thus, fertilizer 1 inch to the side of seed supplied more phosphorus to the oat plants than that closer to the seed except at the very early growth stages.

The influence of depth can be noted from the linear component b_2 and the quadratic component b_{22}. Since the quadratic component was not significantly different from zero, the influence of depth was essentially linear over the range tested. The linear component was not significantly different from zero at the 14-day stage, but was highly significant and positive at the 28- and 42-day stages. This indicates that, within the range tested, the fertilizer phosphorus absorption increased linearly at these two latter stages as the depth of placement increased. At the 58-day stage, however, the linear component, although not significant, had become negative, indicating a tendency for the absorption to decrease as the depth increased. The degree of the influence of depth can be seen in the contour lines in Figure 2. At the 28-day stage the absorption from the fertilizer placed 3 inches below the seed was approximately 50 per cent greater than from fertilizer at seed level or above. At the 58-day stage the absorption decreased considerably with the increasing depth of fertilizer placement at the 0 inch horizontal distance, decreased slightly at the 1- and 2-inch distances but increased at the 3- and 4-inch distances.

The change in the influence of horizontal distances and depth with time points out the need for time-absorption curves to properly evaluate the efficiency of fertilizer placements. The change in the influence of distance with time can be readily explained on the basis of progressive root development. The change in influence of depth with time is more difficult to explain. It appears that the absorbing root surfaces developed at lower

depths during the first few weeks but then developed closer to the surface. It is thought that differences in moisture tension between the upper and lower levels would not be sufficiently large to cause this change in rooting pattern. The restricted volume for root growth in the pot may be a factor although it is difficult to explain why the roots would develop in the upper layers when restricted rather than throughout the pot or around the edges. It is possible that the concentrated root growth in the pot imposed oxygen deficiencies or carbon dioxide toxicities at the greater depths. This phenomenon will require more study to determine if it is the natural rooting habit of the plant or one imposed by artificial conditions.

The influence of nitrogen (b_3) was not significant at the 14-day stage, but was highly significant and positive at the remaining stages, indicating that the fertilizer phosphorus absorption increased with increasing rates of nitrogen. Since the quadratic component (b_{33}) was not significant, the influence of nitrogen was essentially linear within the range tested. The increase in fertilizer phosphorus absorption with increased nitrogen was much greater than the increase in dry weight of tops, suggesting a chemical interaction or physiological influence of nitrogen and phosphorus in the band resulting in an increased absorption of the fertilizer phosphorus.

None of the interaction coefficients was significant although the horizontal distance x nitrogen and depth x nitrogen at the 42-day stage and the horizontal distance x depth interaction at the 58-day stage approached significance. The latter interaction can be seen in Figure 2. Fertilizer phosphorus absorption decreased greatly with increased depth at the 0 horizontal distance but increased at the 3-inch horizontal distance.

The values of R^2 shown in Table 2 indicate that the per cent of the variability accounted for by the regression equations was over 80 per cent at the first two determination dates, declined slightly at the third date and was 51.7 per cent at the final date. This was due to the smaller differences due to treatment at the latter date rather than to increased experimental error. The agreement between the calculated and experimental values in Figure 2 also indicates the goodness of fit of the derived equations. In general, the agreement is considered satisfactory although there are some values which differ considerably, notably those for the placements with the seed at the 14-, 42-, and 58-day stages. At the 14-day stage, absorption by the seed rather than by the roots may account for the difference. At the 42- and 58-day stages, absorption from the seed placement was approximately 50 per cent higher than that calculated. This cannot be satisfactorily explained at present but is most likely indicative of the amount of absorbing root surface near the seed.

Plant Weight after 58 Days

The regression coefficients for oven-dry weight of tops (grain plus straw) are shown in Table 5. The component of variance for lack of fit was non-significant for all criteria shown in Table 5. The only significant coefficient was the linear component for nitrogen rate. The plant weight increased with increasing nitrogen rate. The lack of yield response to the placement variables indicates that phosphorus was not limiting growth with any placement.

TABLE 5. — COEFFICIENTS OF REGRESSION EQUATIONS EXPRESSING PLANT WEIGHT, TOTAL P CONTENT AND PER CENT P DERIVED FROM FERTILIZER AT THE 58-DAY STAGE AS A FUNCTION OF HORIZONTAL DISTANCE AND DEPTH OF PLACEMENT AND RATE OF NITROGEN

Coefficient	Plant weight (gm./pot)	Total P Content		% P derived from fertilizer
		%	mgm./pot	
b_0	4.7880	0.3018	14.4331	51.8049
b_1	−0.0500	0.0062	0.1119	−4.4388*
b_2	−0.0956	0.0028	−0.1331	−1.4131
b_3	0.1788*	−0.0154**	−0.1638	8.3650**
b_{11}	−0.0864	0.0013	−0.2044	−2.3273*
b_{22}	−0.1032	−0.0043	−0.4906*	1.6334
b_{33}	−0.0357	−0.0005	−0.1444	0.9334
b_{12}	0.0000	−0.0059	−0.3112	4.3688*
b_{13}	0.1438	0.0047	0.6450	−2.6850
b_{23}	0.0512	0.0061	0.1825	−0.7475
R^2	0.547	0.306	0.271	0.772

*—Significant at .05 probability level
**—Significant at .01 probability level
R—Multiple correlation coefficient

Total P Content

The regression coefficients shown in Table 5 indicate that there was very little influence of placement on either per cent phosphorus or total phosphorus per pot in the oat tops. This is also shown by the very low values for R^2. The quadratic component for depth was significant in the case of the total phosphorus per pot which indicates a curvilinear influence of depth of placement on this variable. Increasing the nitrogen rate significantly decreased the total per cent P in the tops at the 58-day stage. This is probably due to a dilution effect from the increased plant growth obtained with increased nitrogen rates. The total phosphorus in the tops was also decreased with increased nitrogen rates although not significantly. Since the higher nitrogen rates increased the fertilizer phosphorus content but decreased the total, the increased absorption of fertilizer phosphorus was accompanied by a decreased absorption of the soil phosphorus. It is likely, however, that at earlier growth stages, when the soil phosphorus absorption is small relative to fertilizer phosphorus the total phosphorus content would also increase with increasing nitrogen rates.

Per Cent P Derived from the Fertilizer

The per cent of the plant phosphorus that was derived from the fertilizer was significantly influenced by horizontal distance and nitrogen rate as indicated by the regression coefficients shown in Table 5. Both the linear and quadratic components for horizontal distance were significant and negative. This indicates that the influence of horizontal distance on per cent of the phosphorus derived from the fertilizer was the same as the influence of distance on fertilizer phosphorus absorption, the per cent increasing with the first increments of distance then decreasing. Nitrogen rate had a highly significant, positive influence on the per cent of the phosphorus derived from the fertilizer again corresponding to the influence

on fertilizer phosphorus absorption. Since nitrogen increased the fertilizer phosphorus absorption and decreased the total, the per cent of the phosphorus derived from the fertilizer would necessarily increase. The interaction of horizontal distance and depth was significant. When fertilizer was placed 1 inch to the side of the seed, the per cent of the phosphorus derived from the fertilizer decreased with increased depth, but when placed 3 inches away the per cent derived from the fertilizer increased with increasing depth. This again appears to be due to the influence of placement on absorption of fertilizer phosphorus rather than of soil phosphorus.

The data obtained in this study indicate the necessity for a greater understanding of the physiological aspects of soil fertility. It is apparent that the stage of development of a plant has an influence on the relative ability of the plant to obtain nutrients from different zones. Thus, in selecting the optimum fertilizer placement, consideration must be given to the nutrient requirements of the plant at the various stages of growth. If the phosphorus requirement of the oat plant is greatest during the seedling stage, the data presented indicate that the fertilizer should be placed with or directly below the seed. Fertilizer at the side of the seed was a poor source of phosphorus at this stage. During the period of rapid growth, fertilizer 1 inch to the side and 2 or 3 inches below the seed was most available to the plants. At the period of seed production, a placement with the seed resulted in greatest absorption of fertilizer phosphorus. No single placement resulted in the greatest fertilizer phosphorus absorption at all three stages. Thus selection of the most effective placement will depend on which stage of growth is most critical.

The central composite design is relatively new, particularly in biological experimentation. The authors are of the opinion that the design has permitted effective depiction of the relationships among the factors considered in this study with a markedly reduced number of experimental units relative to the complete factorial. However, they are not prepared to advocate extensive use of the design because it has not as yet been critically compared with other designs.

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COMPOSITE DESIGNS IN AGRICULTURAL RESEARCH[1]

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ABSTRACT

An experiment was conducted in the greenhouse using tomato plants for testing response to nitrogen, phosphorus and potassium on North Gower clay loam and Castor silt loam.

Two designs were used to assess this response, a factorial and a composite design. There was general over-all agreement in results obtained by the two methods. The limitations of the composite design and difficulty in interpretation are discussed.

It is suggested that composite designs be used in agricultural research with some caution. With only three factors under test, the standard factorial is preferred.

INTRODUCTION

There has been some interest recently in the use of composite designs for experimental work in agriculture, e.g. Baird and Fitts (1), and Moore *et al.* (8). These designs were developed by Box (2, 3, 4, 5) for use with material of low variability and where a sequential procedure was possible. The experimental material in agricultural research is relatively more variable than that originally used by Box and Wilson (5), and in addition the application of sequential statistical procedures to field experiments is difficult. In view of the different approach in many aspects of agricultural research from that possible in the so-called "exact" sciences, it seems desirable to examine closely a technique developed for use in these sciences before applying it to research work in agriculture.

It was, therefore, decided to carry out an investigation on two soil types, using both a second order composite design with three factors and a 3^3 factorial design, in order to compare the relative merits of the two designs. The experiments were carried out in the greenhouse at Ottawa.

MATERIALS AND METHODS

Analysis of the two soil types used in this investigation gave the following results:

Soil type	pH	O.M. (%)	Base exch. cap. (me./100 g.)	Exch. K (me./100 g.)	$NaHCO_3$ sol. P (p.p.m.)
Castor silt loam	7.1	1.91	7.2	0.08	2.9
North Gower clay loam	7.1	5.60	25.3	0.32	8.0

Tomato plants were used as the indicator crop and were grown in half-gallon glazed pots. The appropriate quantities of N, P and K were mixed with 3 pounds of soil before placing in the pot. The plants were selected for uniformity at about 4 inches in height and three were transplanted into each pot from sand where they had all grown under uniform conditions with a weak nutrient solution.

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The rates of nutrients used for the two soils along with their coded values for the x_1, x_2 and x_3 scales in the composite design are:

Lb. per acre	Castor					North Gower				
	*		*		*		*	*	*	
N (x_1)	0	50	150	250	300	0	50	150	250	300
P_2O_5 (x_2)	0	80	240	400	480	0	80	240	400	480
K_2O (x_3)	0	70	210	350	420	0	70	210	350	420
Coded values	−1.5	−1	0	+1	+1.5	−1.5	−1	0	+1	+1.5

The rates of nutrients were selected from previous experience with the soils.

The 15 treatment combinations necessary for the composite design are the first 15 given in Table 1. The rest of the treatments in this table are the additional treatments used for the 3^3 factorial experiment on the North Gower clay loam; a total of 33 was required for each replication. The total number of pots required for a single replication of the combined composite-plus-factorial set-up on the Castor silt loam was 35. It will be noticed that with the latter the composite design is entirely "enclosed" in the factorial design, while with the North Gower soil the factorial is "enclosed" within the composite set of treatments; reference to the table giving the levels of application of the three nutrients, and possibly plotting on a graph the coded dressings used for two of the nutrients, will make these statements clearer.

Two replications were used for each soil, and the pots in each replicate were completely randomized. The plants were grown for 50 days after transplanting, and during this period the pots in each replicate were rotated within the replicate at least twice weekly in order to minimize positional effects. This obviated to some degree the necessity of using incomplete blocks, which with a "combined" design of this type would have been difficult.

At harvest both tops and roots were taken. The roots were first separated from the bulk of the soil, dipped in water, and then gently washed in a wet sieving machine for 10 minutes.

RESULTS

The yields of tops obtained from the North Gower soil are given in Table 1. The method of analysis will be very briefly summarized using these results; full descriptions of the methods of analysis of both the factorial and the composite designs have been given by Cochran and Cox (6).

The first 6 treatments in Table 1 form part of the composite design only; the next 9 treatments form part of both the composite and factorial designs; the last 18 treatments form part of the factorial scheme only.

The analysis of the composite design is basically a multiple regression problem; we are attempting to fit a surface with an equation:

$$y_i = b_0 + b_1x_{1i} + b_2x_{2i} + b_3x_{3i} + b_{11}x_{1i}^2 + b_{22}x_{2i}^2 + b_{33}x_{3i}^2 + b_{12}x_{1i}x_{2i} + b_{13}x_{1i}x_{3i} + b_{23}x_{2i}x_{3i} \quad (1)$$

TABLE 1.—YIELDS OF TOMATO TOPS ON NORTH GOWER CLAY LOOM

Nutrient treatment			Coded levels			Yields of tops		
N	P_2O_5	K_2O	x_1	x_2	x_3	Rep. 1	Rep. 2	Total
lb. per acre						gm. dm per pot		
0	240	210	−1.5	0	0	5.00	5.14	10.14
300	240	210	1.5	0	0	12.71	14.29	27.00
150	0	210	0	−1.5	0	5.52	4.20	9.72
150	480	210	0	1.5	0	12.59	10.43	23.02
150	240	0	0	0	−1.5	9.96	12.24	22.20
150	240	420	0	0	1.5	10.23	10.38	20.61
150	240	210	0	0	0	9.78	9.40	19.18
50	80	70	−1	−1	−1	6.82	7.83	14.65
50	80	350	−1	−1	1	7.08	6.21	13.29
50	400	70	−1	1	−1	8.85	8.58	17.43
50	400	350	−1	1	1	6.97	6.07	13.04
250	80	70	1	−1	−1	9.49	7.80	17.29
250	80	350	1	−1	1	7.80	8.85	16.65
250	400	70	1	1	−1	16.25	10.83	27.08
250	400	350	1	1	1	15.48	14.56	30.04
50	80	210				5.38	6.78	12.16
50	240	70				5.90	7.42	13.32
50	240	210				6.44	6.80	13.24
50	240	350				5.68	5.22	10.90
50	400	210				7.03	7.70	14.73
150	80	70				9.23	8.50	17.73
150	80	210				6.52	9.82	16.34
150	80	350				8.08	7.31	15.39
150	240	70				8.86	11.56	20.42
150	240	350				12.62	11.63	24.25
150	400	70				13.68	10.58	24.26
150	400	210				11.90	11.50	23.40
150	400	350				13.00	14.03	27.03
250	80	210				8.38	9.48	17.86
250	240	70				13.89	12.58	26.47
250	240	210				12.60	14.79	27.39
250	240	350				13.23	13.51	26.74
250	400	210				14.40	15.58	29.98

By coding the nutrient applications as −1.5, −1, 0, +1, +1.5, the computations are greatly simplified. The linear effects, and linear x linear interactions, are all orthogonal to each other and to curvature effects. The curvature effects in these experiments are not orthogonal to each other. This has been the case with composite designs in a number of experiments in the past, but by judicial choice of levels of application these effects can also be made orthogonal (9).

Emphasis has previously been put upon obtaining a response surface using all treatment variables in the equation, without testing the statistical significance of the separate effects [De Baun, (7)]. The separation usually suggested [Cochran and Cox, (6)] is merely (i) a test of a planar response surface, and then (ii) the additional benefit of using a second order response surface. It is not advisable to carry through with this approach in agricultural research.

We have here separated out all orthogonal terms, and the full analysis is given in Table 2A. The linear effects of both N (x_1) and P (x_2) are

TABLE 2.—ANALYSIS OF VARIANCE OF YIELDS OF TOMATO TOPS FROM NORTH GOWER CLAY LOOM

A. COMPOSITÉ DESIGN

Source of variation	df	s.s.	m.s.
Total	29	296.50	
Regression on x_1 (linear effect of N)	1	134.28	134.28***
Regression on x_2 (linear effect of P)	1	83.39	83.39***
Regression on x_3 (linear effect of K)	1	1.35	1.35
Regression on x_1x_2 (linear N x linear P)	1	26.65	26.65**
Regression on x_1x_3 (linear N x linear K)	1	4.07	4.07
Regression on x_2x_3 (linear P x linear K)	1	0.02	0.02
Curvatures (quadratic effects of N, P & K)	3	12.85	4.28
Lack of fit	5	8.32	1.66
Replications	1	1.99	1.99
Error	14	23.58	1.68

B. FACTORIAL DESIGN

Source of variation	df	s.s.	m.s.
Total	53	511.66	
N — linear	1	259.96	259.96***
— quadratic	1	10.54	10.54*
P — linear	1	119.65	119.65***
— quadratic	1	2.22	2.22
K	2	0.56	0.28
N P — linear x linear	1	38.00	38.00***
— remainder	3	16.35	5.45*
N K — linear x linear	1	4.82	4.82
— remainder	3	6.99	2.33
P K — linear x linear	1	1.34	1.34
— remainder	3	0.57	0.19
N P K	8	9.50	1.19
Error	26	41.17	1.58

*Significant at 5% level of probability
**Significant at 1% level of probability
***Significant at 0.1% level of probability

highly significant, and their interaction is also significant. Potassium (x_3) had a negligible effect, and its interactions with N and P were not important; it may, therefore, be omitted from further consideration in the present experiment. It is doubtful, also, whether it is worthwhile including in future experiments.

Had we followed the advice of others, and tested the significance of linear terms (having a mean square of 73.01 with 3 d.f.) we would have obtained high significance. In addition, the second order terms (having a mean square of 7.26 with 6.d.f.) are significant almost at the 1 per cent level of probability. We would then have concluded that it was necessary to include all three first order terms and all six second order terms in the equation expressing the relationship between yield and levels of application of nutrients.

TABLE 3. — VALUES OF THE COEFFICIENTS IN EQUATION *1* AS ARRIVED AT WITH THE FACTORIAL AND COMPOSITE DESIGNS

Coefficient	North Gower clay loam				Castor silt loam			
	Tops		Roots		Tops		Roots	
	Factorial	Composite	Factorial	Composite	Factorial	Composite	Factorial	Composite
b_0	10.59	9.58	1.476	1.401	6.46	6.39	1.054	1.036
b_1	2.69	2.32	0.296	0.298	1.74	2.72	0.173	0.220
b_2	1.82	10.83	0.301	0.267	1.98	2.00	0.338	0.276
b_3	−0.04	−0.23	−0.060	0.006	0.24	−0.45	0.055	−0.091
b_{11}	−0.94	−0.13	−0.111	0.059	−0.04	0.35	0.053	0.089
b_{22}	−0.43	−0.62	−0.104	−0.134	−1.19	−1.09	−0.177	−0.186
b_{33}	0.21	0.50	0.069	−0.048	−0.04	0.06	−0.053	−0.064
b_{12}	1.26	1.29	0.126	0.115	1.00	1.44	0.094	0.078
b_{13}	0.45	0.50	0.038	0.058	0.40	0.52	0.093	0.068
b_{23}	0.24	0.04	0.005	0.009	0.18	0.42	0.045	−0.016
	Standard errors							
b_i	0.21	0.26	0.029	0.044	0.07	0.29	0.034	0.049
b_{ii}	0.36	0.33	0.051	0.057	0.08	0.37	0.039	0.063
b_{ij}	0.26	0.32	0.036	0.056	0.06	0.36	0.028	0.062

Note: Underlining denotes significance at the 5% level (at least).

The curvature effects still present a slight problem even in this more detailed breakdown. If the first 6 treatments in Table 1 had used nutrient applications which could have been coded with 1.215 in the place of 1.5, all three curvature effects would have been orthogonal to each other, and the present difficulties would have been circumvented.

Application of t-tests to the three partial regression coefficients determining curvature indicate no significance. It must be remembered, however, that in these tests we are merely testing whether there is a *further* significant reduction in the residual variance *after* all other "independent" variable have been taken into account. When the "independent" variables are not orthogonal, anomalies can arise. In the present case, for example, we have decided that potassium is unimportant, and when it is dropped from consideration here, it is found that the curvature effect of phosphate is significant at the 5 per cent level of probability.

All the coefficients in equation *1* were in fact calculated and are shown in Table 3. The main point of this table is to demonstrate the similarity in the results obtained by the two experimental schemes for all of the variables measured. It also serves to emphasize the fact that the results from the factorial layout can be used to calculate a response surface of the same form as that obtained from results of the composite experiment. It is for this reason we are here using the term "composite" design rather than "response surface" design. The results given in this table speak for themselves and it is unnecessary to itemize all points of similarity.

With reference to the yields of tops from the North Gower soil, the similarity is also demonstrated in the analyses of variance given in Table 2. The highly significant linear effects of N and P are demonstrated in both tables, as is also the strong positive linear x linear interaction between N and P. The significance of the 3 d.f. for the "remainder" of the N P interaction (Table 2B) is due to the significance of the linear N x quadratic P interaction and is a manifestation of the same effect which showed up in the linear x linear part of the N P interection. It is caused by the fact that the linear effects of N at the two higher levels of P are close to each other and both very much higher than the linear effect of N at the nil level of P.

There was no demonstrable effect due to potassium in either design.

There is one apparent slight disagreement in the results of the two analyses in that the curvature effect of N is significant in the factorial set-up whereas it is the curvature effect of P which is significant in the composite scheme. The disagreement, however, is not quite as great as it would seem. The curvature of P is significant and negative at the high level of N in the factorial design, whereas it is positive (but not significant) at the nil level of N. This is another way of putting into words the fact that the linear N x quadratic P interaction is significant. It is difficult to see why the curvature effect of N in the composite design should not be significant, but it is possibly due to a similar sort of effect. This difficulty of visualizing what in fact is happening when the composite design is used is one of the disadvantages of that design.

The data given in Table 3 for the Castor soil should be treated with some caution due to the large relative differences in weight of plants, and

TABLE 4.—YIELDS OF TOMATO TOPS FROM CASTOR SILT LOAM

A. COMPOSITE DESIGN — 2 REPLICATES

Treatments — lb./a.			Yields — gm. dm per pot		
N	P_2O_5	K_2O	Rep. 1	Rep. 2	Total
50	80	70	3.70	3.80	7.50
50	80	350	2.94	2.11	5.05
50	400	70	4.94	3.92	8.86
50	400	350	2.31	2.03	4.34
250	80	70	5.68	5.29	10.97
250	80	350	3.31	3.09	6.40
250	400	70	10.57	11.83	22.40
250	400	350	16.82	9.84	26.66
150	240	210	5.86	7.24	13.10
0	240	210	2.69	2.03	4.72
300	240	210	13.20	10.09	23.29
150	0	210	0.91	0.82	1.73
150	480	210	6.50	7.09	13.59
150	240	0	6.85	7.28	14.13
150	240	420	6.01	5.53	11.54

B. FACTORIAL DESIGN — 1 REPLICATE

Rates of nutrients (lb./a.) and yields (gm. dm per pot)

N	0			150			300		
P_2O_5	0	240	480	0	240	480	0	240	480
K_2O									
0	0.80	2.53	2.78	0.71	6.85	6.00	0.33	6.91	7.70
210	0.87	2.69	2.02	0.91	5.86	6.50	0.42	13.20	11.19
420	0.92	1.66	1.61	0.52	6.01	6.19	0.05	10.88	12.43

associated differences in variability, for certain of the different levels of N and P. This can be seen from the data in Table 4B, the data from the factorial section of the design. Only one replication of the factorial design is presented here, because it has been argued elsewhere (9) that the two replications of a composite design with 30 plots are no more informative than the single replication of a factorial design.

It is possible, of course, from both sets of data to calculate the coefficients for equation *1*, but this is not the end of the matter: it is necessary to make decisions as to which factors are important and which are not. The human mind can visualize a problem in two dimensions quite easily, but finds it difficult to visualize a problem in three or more dimensions. With the factorial data the over-all problem is reduced fairly readily to a number of two-dimensional problems where it is easy to see what is happening; with the composite design this is more difficult.

The following points can be made after a visual examination of the factorial data:

1) With no P the level of yield is extremely low; one would expect a different error to be associated with this level from that associated with, say, the higher applications of both N and P.
2) With no P, there appears to be a tendency for the high level of N to have a harmful effect.
3) With P, but no N, the level of yield is somewhat improved, but is still considerably lower than that obtained with both N and P.
4) There is virtually no difference between the two levels of added P.
5) There is a strong positive interaction between N and K at the higher levels of N and P; i.e., K has a beneficial effect when N is at 300 and P is at 240 or 480, whereas with lower dressings of N and P, K had virtually no effect.

All of these points are confirmed in the analysis of the two replications of the factorial data.

A visual inspection of the data from the composite arrangement does not lead to such a "tidy" nor such a comprehensive set of conclusions. The importance of the effects of N and P is immediately obvious, of course, but in summarizing these one cannot say very much more than

1) Yields are low with N at 0 or 50.
2) Yields are low with P at 0 or 80.
3) Yields are very much higher when both N and P are over 200; the magnitude of the increase in yield would indicate a strong interaction effect.

The analysis of variance confirms these conclusions, and, in addition, brings to light the negative curvature in response due to P. All of the other points, however, are missed. The suggestion of a possible negative response to K when N or P was low was not confirmed by the analysis of variance.

DISCUSSION

The first point to note is that the factorial experiment may be used to determine a response surface (or regression equation) of exactly the same form as that developed from the composite design. The introduction of composite designs with the great emphasis put on the resulting response surface has tended to make research workers forget that the same objective may be achieved with the standard factorial. The advantage of this latter is that no such functional relationship is assumed at the outset.

Another point worth mentioning is the fact that the five levels of each factor which are tested in the composite design do not constitute an advantage over the three levels of the factorial. They do not necessarily imply that a greater range of levels is tested; exactly the same range of levels is tested on the Castor soil. Nor do they give a better insight into the form of the response surface, because the form assumed is that given in equation *1*.

When only three factors are involved, the composite design offers no real advantage over the factorial. If the number of factors is increased, however, the composite design requires fewer plots than the factorial scheme, and this is particularly marked with five or more factors (9). A disadvantage creeps in if orthogonal designs in incomplete blocks are not used, in that the number of plots per replication become large, and positional effects may become important.

We have here examined results from a greenhouse experiment, but many of the comments made can be applied to agricultural research in general.

ACKNOWLEDGEMENTS

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THE EFFECT OF NITROGEN FORM AND SOIL TEMPERATURE ON THE GROWTH AND PHOSPHORUS UPTAKE OF CORN PLANTS GROWN IN THE GREENHOUSE[1]

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ABSTRACT

In a greenhouse experiment, corn seedlings were grown over a 2-week period in soil and in sand-resin media. Nitrate and ammonium nitrogen was applied at rates from 25 to 800 p.p.m., and phosphorus at 50 and 200 p.p.m. Soil temperatures of 60°, 70°, and 80°F. were used.

It was concluded that growth and phosphorus uptake reached a maximum when approximately 200 p.p.m nitrogen was applied. Total dry matter production in roots was inversely related to nitrogen application, and to total phosphorus uptake. In soil, the ammonium form of nitrogen tended to be more effective than the nitrate form in increasing phosphorus uptake. In sand-resin with an absence of nitrification, the opposite was found. Significant interactions were found between nitrogen rate and form. Increasing soil temperature from 60° to 80° F. enhanced the effect of nitrogen on phosphorus uptake.

INTRODUCTION

Soil reaction (13), form of applied nitrogen (10), nature of the complementary ion (6), and temperature of the growth medium (12) have been reported to influence the effect of nitrogen on phosphorus uptake. Furthermore the placement of one nutrient relative to the other may also influence this effect (9).

The mechanism whereby nitrogen may increase phosphorus uptake may be explained on the basis of direct chemical effects or indirect physiological effects. The direct effects include increases in the solubility of phosphorus, due to the presence of nitrogen salts (4), or to residual acidity (13). The indirect effects include increases in the anion-cation ratio in the plant (7), in root proliferation (9), in cation exchange capacity of roots (8), or in root efficiency (3). Excess nitrogen, on the other hand, may decrease root proliferation through excess auxin production (2).

The object of this study was to investigate the effect of level and form of nitrogen on growth and phosphorus uptake by corn at different soil temperatures.

MATERIALS AND METHODS

A fine-textured soil, low in nitrogen and phosphorus, and obtained from the B, horizon of a Haldimand clay profile, was used as the growth medium in the first phase of the study. Aliquots of nitric acid, ammonium hydroxide, and phosphoric acid were added to 500-gram portions of the air dry soil to supply nitrogen at 25, 50, 100, 200, 400, and 800 p.p.m, and phosphorus at 50 and 200 p.p.m. A commercial soil-stabilizing agent, "Merloam"[3], was added at the rate of 0.28 per cent by weight, and the soil mixed thoroughly before placing in pint polythene containers. The soil was brought to its moisture equivalent at planting time and further additions of distilled water were made as indicated by weight.

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[2]Former Graduate Student, and Associate Professor, respectively.
[3]Monsanto Chemical Co., St. Louis, Missouri.

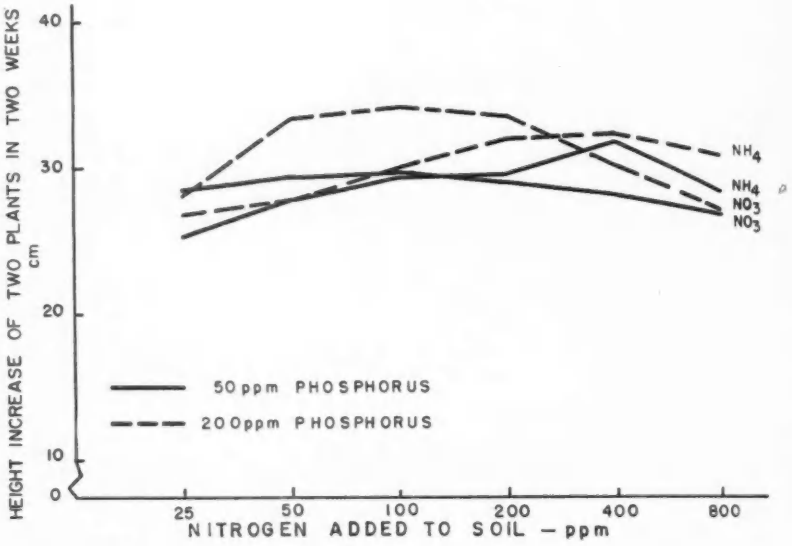

FIGURE 1. Effect of nitrogen and phosphorus level, and nitrogen form, on increase in height of corn plants in soil over a 2-week interval.

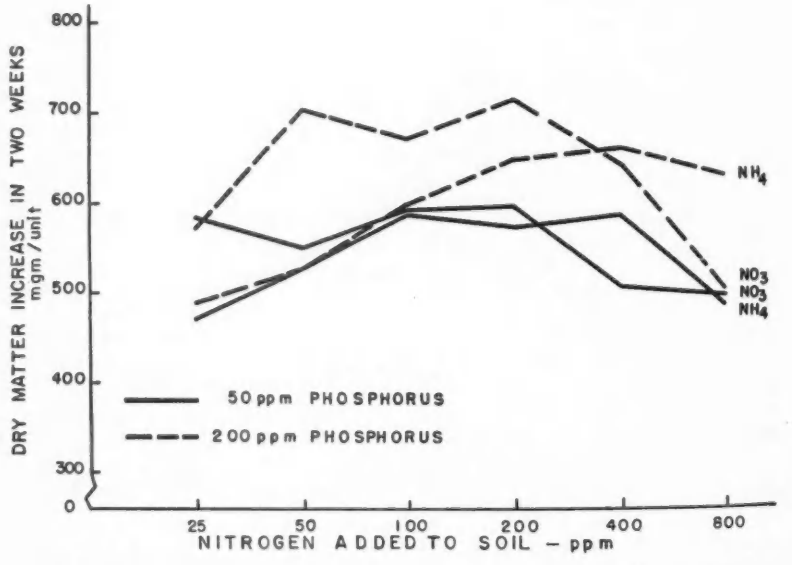

FIGURE 2. Effect of nitrogen and phosphorus level, and nitrogen form, on increase in total dry matter in top growth of corn plants grown in soil over a 2-week interval.

Kernels of monocross corn (Funks G-30, Female) were placed to germinate for 2 days on moist vermiculite, and then planted in half-pint cartons containing approximately 40 grams of perlite and a cheesecloth liner. The cultures were watered 2 days prior to planting and every second day after planting. Each culture contained two plants. At the end of 2 weeks, plants started in this manner attained an average height of 5 to 10 centimetres. The root masses at the bottoms of 72 containers selected for uniformity were exposed at this time and placed on the treated soils in the polythene containers. The object of this technique, similar to that of Stanford and De Ment (11), was to obtain uniform cultures with a mass of well-developed roots.

Uniform soil temperatures of 60°, 70°, and 80°F. were maintained by placing the cultures in Styrofoam insulated water baths. The water was circulated continuously and its temperature was controlled thermostatically. Aluminum foil was placed over the cultures with openings for the plants. Greenhouse temperatures were held close to 85°F. during the day and 60°F. during the night. Incandescent lights were used to augment daylight and provide an 18-hour day. The statistical design was a split plot with temperature as the main treatment, and nitrogen form and phosphorus and nitrogen rates as sub-treatments.

At the end of a 2-week period the 72 cultures, constituting one replication, were harvested. In the course of two successive 2-week periods, two additional replications were obtained, giving a total of 216 units. The total combined heights of the two plants, and the total dry matter in tops and roots in each culture, were measured. The total phosphorus in

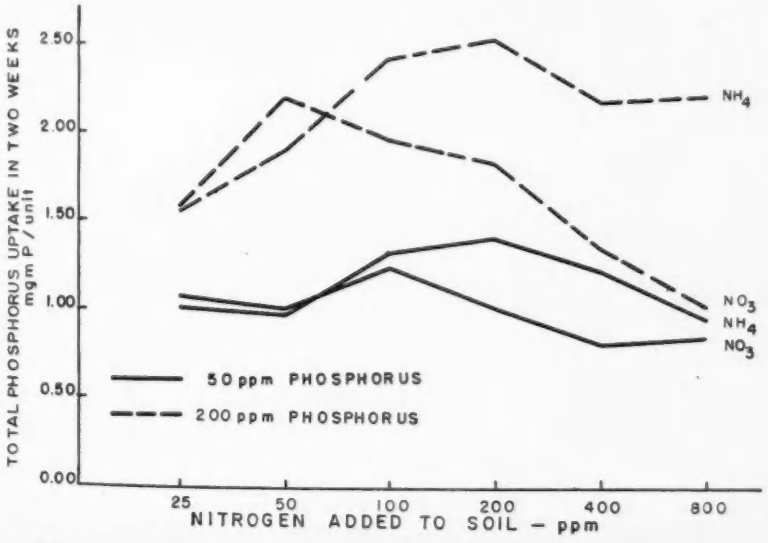

FIGURE 3. Effect of nitrogen and phosphorus level, and nitrogen form, on total phosphorus taken up by corn plants in soil over a 2-week interval.

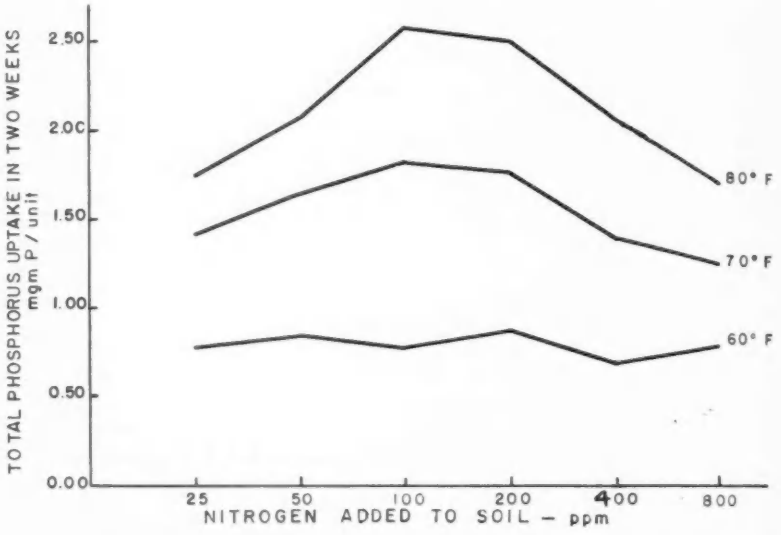

FIGURE 4. Effect of temperature and nitrogen level on total phosphorus taken up by corn plants in soil over a 2-week interval.

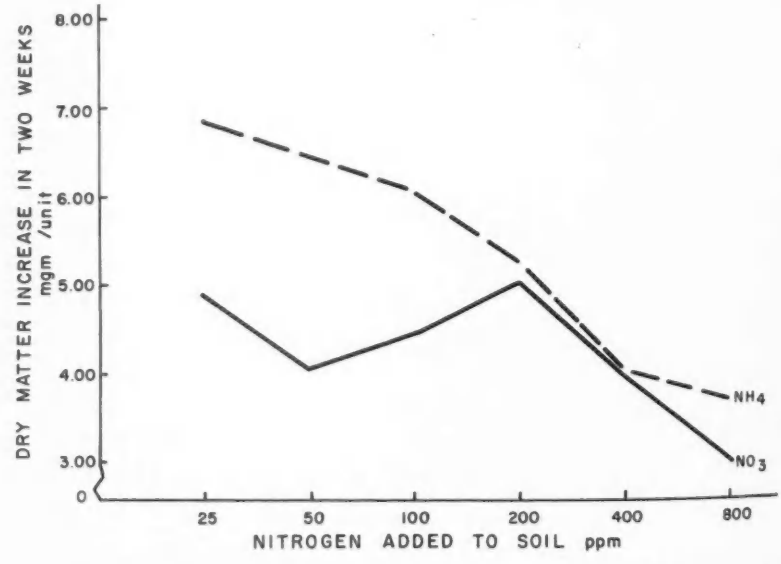

FIGURE 5. Effect of nitrogen level and form on the increase in total dry matter in roots of corn plants grown in soil over a 2-week interval.

tops was determined by the method of Kitson and Mellon (5). Corresponding measurements for similar plants at the beginning of the 2-week period were subtracted from the final values and only the increase for the period is reported.

The second phase of the study was designed to control nitrification, pH, and complementary ion effects. In this instance, soil was replaced by quartz sand mixed with different nutrient-charged synthetic exchange resins along with potassium, calcium, magnesium and trace elements in nutrient solution. Amberlites IRC-50 and IR-4B were chosen as the ammonium, and the nitrate and phosphate ion resins, respectively.

RESULTS AND DISCUSSION

All plants established well and exhibited a high degree of uniformity. The reaction of the soil at the beginning of the 2-week interval was slightly below pH 6.0, while that of the sand-resin mixture was approximately pH 7.0. At the end of the 2-week period only slight changes in pH could be detected and these were considered to have had no physiological influence on growth or uptake of nutrients during this period.

Because of certain interactions between main and sub-treatments, statistically significant either at the 1 or 5 per cent level, direct conclusions from these treatments alone cannot be drawn. However, some general observations may be made. Increasing temperatures increased growth and nutrient uptake linearly in accordance with the observations of Willis *et al.* (12). Figures 1, 2, 3, and 4 illustrate that nitrogen rates gave a curved (quadratic) regression for increases in height, dry matter in top growth, and total phosphorus uptake. Growth, and particularly phosphorus uptake, were stimulated by nitrogen up to a maximum value, and were retarded with higher nitrogen rates.

The effect of nitrogen rate on the weight of dry matter in roots is shown in Figure 5. It supports Bosemark's (2) observations of declining linearity with increasing nitrogen rate. Ammonium nitrogen produced more dry matter than nitrate nitrogen at the lower rates of application. It appears in this study that nitrogen rates as low as 25 p.p.m were critical. At the same time, growth and phosphorus uptake by tops did not show a corresponding decline. It must be noted, however, that active absorbing surface may vary independent of root weight and it was observed in this work that roots in ammonium-treated soils tended to be more finely branched, particularly at the higher nitrogen levels, than those in nitrate-treated soils. In contrast to roots, nitrogen rates of 200 p.p.m appear critical for top growth.

For all measurements, except total dry matter in roots, the interaction of nitrogen rate x nitrogen form x phosphorus rate was significant and is illustrated graphically in Figures 1, 2, and 3. The change in effectiveness of the two nitrogen forms with rate was more pronounced at the 200-p.p.m phosphorus rate than at the 50-p.p.m rate. At the lower nitrogen rates, nitrate nitrogen tended to be superior to ammonium nitrogen, while at the higher rates the opposite relationship prevailed. With height and dry matter increase, the reversal occurred between 200 and 400 p.p.m. With

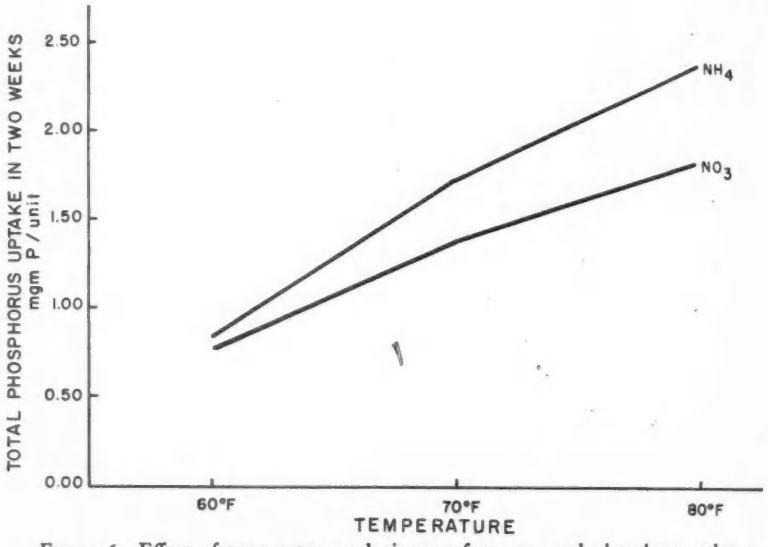

FIGURE 6. Effect of temperature and nitrogen form on total phosphorus taken up by corn plants in soil over a 2-week interval.

phosphorus uptake, ammonium nitrogen was superior above 100 p.p.m but the difference between forms below this rate was considered insignificant. The highly significant nitrogen rate x nitrogen form interaction may have been due to preferential uptake of nitrate nitrogen over that of ammonium nitrogen, as noted by Baldwin and Ketcheson (1). Accordingly, the critical nitrogen level appears to have been reached at a lower nitrogen rate when nitrate was used. At higher rates of application, the critical level appears to have been reached regardless of nitrogen form.

From Figure 4, it is evident that temperature influenced phosphorus uptake, and that the differences in phosphorus uptake between temperatures were more pronounced at the 100-p.p.m nitrogen rate than at higher or lower nitrogen rates. This curved (quadratic) regression of nitrogen on phosphorus uptake was accentuated with increasing soil temperature. Figure 6 shows that ammonium nitrogen caused a greater phosphorus uptake than did nitrate nitrogen. This effect was more pronounced as soil temperature increased. However, other workers have shown that, with older plants, nitrate may be superior to ammonium nitrogen (10).

Plants grown on the sand-resin media, on the contrary, showed that nitrate nitrogen was superior to ammonium nitrogen in terms of all measurements made, supporting the observations of Naftel (10). The uptake of phosphorus is shown in Figure 7. No nitrate nitrogen was found by analysis in either cropped or uncropped sand-resin media treated with ammonium nitrogen. The presence of even a small amount of nitrate with the ammonium, as from nitrification in a soil medium, may account for the apparent superiority of ammonium over nitrate nitrogen as shown in

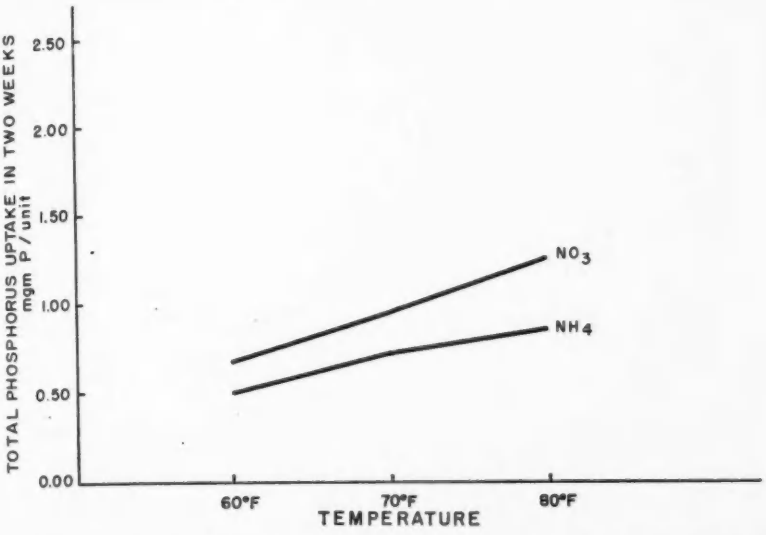

FIGURE 7. Effect of temperature and nitrogen form on total phosphorus taken up by corn plants in sand-resin over a 2-week interval.

Figure 6. The results reported in this study pertain to treatments mixed throughout the rooting medium. Placing the nitrogen and phosphorus in specific bands would present a different situation in respect to growth and nutrient uptake.

CONCLUSIONS

There is an optimum nitrogen level for the growth and uptake of phosphorus by corn plants. Growth and uptake increased with the initial increase in nitrogen application, passed through a maximum at about 200 p.p.m. and declined with higher applications. Total dry matter produced by roots was inversely related to nitrogen application, and to total phosphorus uptake.

In soil, the ammonium form of nitrogen tended to be more effective than the nitrate form in increasing phosphorus uptake. In sand-resin, with an absence of nitrification, the opposite was found. Significant interactions were found between nitrogen rate and form.

Increasing soil temperature from 60°F. to 80°F. enhanced the effect of nitrogen on phosphorus uptake.

The techniques involving sand and synthetic ion exchange resin cultures appeared effective in controlling pH, nitrification, and complementary ion effects.

ACKNOWLEDGEMENT

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EFFECTS OF VARYING LEVELS OF PHOSPHORUS AND POTASSIUM APPLICATIONS ON PRODUCTIVITY, AND BOTANICAL AND CHEMICAL COMPOSITION OF A LADINO CLOVER-TIMOTHY ASSOCIATION[1]

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ABSTRACT

Phosphorus and potassium were applied separately at five levels — 0, 60, 120, 180 and 240 pounds per acre — and in all combinations prior to seeding a ladino clover-timothy mixture. Plots were cut four times per season to a height of 3 inches. Forage yields were obtained during 1954, 1955 and 1956 from a seeding made in 1953 on Coaticook silt loam soil at the Experimental Farm, Lennoxville, Quebec.

Phosphorus fertilization had no significant effect on clover yields but caused distinct increases in timothy yields in 1954 and 1955. Clover yields increased linearly with increasing levels of potassium up to 120 pounds per acre in 1954 and up to 180 pounds in 1955. In 1956, the increase in yields was a linear function of rates of potassium application. Potassium fertilization depressed timothy yields in 1954 but had no effect in 1955 and 1956. The percentage of clover in the harvested forage tended to increase with increasing rates of potassium and to decrease with increasing rates of phosphorus. The reverse was true for timothy. The chemical composition of each forage fraction is also presented.

INTRODUCTION

Ladino clover has become one of the most valuable pasture legumes in Quebec. However, basic information on the soil fertility requirements of ladino clover is very limited. Studies on the effects of varying levels of phosphorus and potassium applications on a ladino clover-timothy mixture under local conditions were initiated in 1953 at the Experimental Farm, Lennoxville, Quebec.

REVIEW OF LITERATURE

Ladino clover requires good fertile soil for best growth. Brown and Munsell (3) showed that a combined application of lime, phosphorus and potassium was the most effective treatment for increasing the yields of ladino clover on an acid soil of low fertility. Midgley (9) reported substantially increased yields of ladino clover from the application of mineral fertilizer on land previously limed. Wakefield *et al.* (13) obtained good response to both phosphorus and potassium applications. Eby *et al.* (7) have shown profitable yield increases from phosphorus but potassium had a more pronounced effect on both the yield and stand of ladino clover. Burger and Sperow (4) reported greater yields of dry matter and protein per acre with several ladino clover-grass mixtures when fertilized with PK than with P alone. Likewise, the contribution of the clover to those yields was highest with the PK treatment. Stewart and Bear (11), and Blaser and Brady (1) obtained increased yields of ladino clover with increasing increments of potassium. Potassium has been recognized by many as the key element for the maintenance of ladino clover stands (2, 3, 7, 10, 11, 15).

[1]Part of a thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy, University of Wisconsin. 1958.

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TABLE 1. — EFFECTS OF VARYING LEVELS OF PHOSPHORUS AND POTASSIUM APPLICATIONS ON THE ADJUSTED FRACTION AND TOTAL YIELDS OF DRY MATTER IN POUNDS PER ACRE FOR EACH HARVEST YEAR

Treatment-lb./acre		Clover fraction				Timothy fraction				Total production**			
		1954	1955	1956	Average*	1954	1955	1956	Average*	1954	1955	1956	Average*
P_2O_5													
	0	2967	378	414	1251	1341	2139	1703	1730	4310	2518	2117	2982
	60	2861	428	455	1249	1443	2146	1616	1736	4314	2573	2072	2987
	120	2970	372	440	1260	1633	2268	1735	1875	4594	2636	2175	3134
	180	2692	372	403	1157	1709	2419	1743	1955	4393	2789	2144	3108
	240	2790	406	348	1181	1703	2396	1744	1950	4498	2807	2092	3133
K_2O													
	0	2097	249	230	858	1657	2256	1628	1842	3736	2497	1858	2695
	60	2738	354	322	1134	1736	2332	1744	1933	4449	2680	2065	3062
	120	3110	409	403	1312	1524	2281	1748	1858	4663	2703	2154	3177
	180	3142	495	477	1373	1477	2179	1720	1793	4630	2682	2196	3171
	240	3193	449	628	1421	1435	2320	1701	1820	4631	2761	2327	3239
Average		2856	391	412		1566	2274	1708		4422	2665	2120	

*The average values reported are the adjusted yields of the 3 years' analysis; they differ slightly from the average data of the 3 harvest years.
**The values reported are the adjusted yields of each year's analysis; they differ slightly from the total yields of both the clover and timothy fractions.

Studies by Jensen (8) showed that the phosphorus content in ladino clover increased linearly with increasing levels of P fertilizer while the K content was not significantly altered. The percentage of K in the clover increased with added increments of this element but the percentage of P was not significantly modified as a result of K fertilization. Jensen (8) reported also that the crude protein content was not significantly affected by P fertilization. Wedin *et al.* (14) obtained significant increases in the P and K contents in ladino clover following PK fertilization, whereas the Ca content was lowered. Brown (2) reported that the concentrations of N, P and Ca in the plant tissue was "not influenced much by variations in K fertilization". Wakefield *et al.* (13) showed that the absorption of potassium by ladino clover increased with the potassium supply, an effect also noted by Blaser and Grady (1), and reported that increasing the potassium application resulted in a slight increase in the calcium content in the clover.

MATERIALS AND METHODS

Studies were carried out on Coaticook silt loam soil with good surface drainage and moderate fertility. The pH of the soil was 5.7. Finely-ground limestone was applied at the rate of 2 tons per acre prior to seeding and worked in by several diskings. An application of 150 pounds of ammonium nitrate and 25 pounds of borax per acre was made over the entire area before seeding.

A quadruple lattice design involving 25 fertilizer treatments was used. Phosphorus and potassium were applied separately at five levels — 0, 60, 120, 180 and 240 pounds per acre — and in all combinations prior to seeding a ladino clover-timothy mixture. No further application of fertilizer was made during the course of the experiment. Oregon certified ladino clover, *Trifolium repens* L., and Climax timothy, *Phleum pratense* L., were seeded at the rate of 2 and 8 pounds per acre, respectively. The clover seed was inoculated. Individual plots were 6 x 20 feet in size.

Vanguard oats, used as a companion crop at the rate of 1½ bushels per acre, and the forage mixture were seeded on June 23, 1953, with a grain drill after the soil had been cultipacked. The oats were cut when heading out and removed from the plots. The regrowth of the companion crop was clipped by mid-August and removed from the experimental area. Dense stands were obtained from all fertilizer treatments and the plots were in excellent condition in the fall.

Forage yields were obtained in 1954, 1955 and 1956. Four cuttings to a height of 3 inches were taken each year. No cutting was made after September 6. One swath was taken through the entire length of each plot. Immediately after cutting, a representative sample was collected from each plot and hand-separated into each of the seeded components (ladino clover and timothy fractions) and into miscellaneous plants (weeds and volunteering useful species). Each forage fraction was first air-dried and then oven-dried to constant weight. Chemical analysis was made on the bulked samples of the clover fraction and of the grass fraction from the four replications of each treatment*.

*Chemical analysis performed at the Analytical Chemistry Research Service, Research Branch, Canada Department of Agriculture, Ottawa.

TABLE 2. — LINEAR AND QUADRATIC EFFECTS OF PHOSPHORUS AND POTASSIUM APPLICATIONS ON THE YIELDS OF DRY MATTER REPORTED IN TABLE 1

	Clover fraction			Timothy fraction			Total production		
	1954	1955	1956	1954	1955	1956	1954	1955	1956
P_L	—	—	—	**	**	—	—	**	—
P_Q	—	—	—	—	—	—	—	—	—
K_L	**	**	**	**	—	—	**	*	**
K_Q	**	**	—	—	—	—	**	—	—
PK_{LL}	**	*	—	—	—	—	—	—	—

**Significant at 1 per cent point
*Significant at 5 per cent point
–Not significant

RESULTS AND DISCUSSION

Yields of Forage

The adjusted yields of dry matter in pounds per acre of the clover fraction, timothy fraction and total production as influenced by varying levels of phosphorus and potassium applications for each harvest year are summarized in Table 1. The linear and quadratic effects of phosphorus and potassium applications on these yields are presented in Table 2.

Clover Fraction

Phosphorus fertilization failed to establish a significant trend in the yields of clover for any one year. On the contrary, potassium fertilization had a marked effect on the yields. Highly significant linear and quadratic trends were found during each harvest year except the quadratic trend in 1956. The yields increased linearly with increasing levels of potassium application up to 120 pounds in 1954 and up to 180 pounds in 1955 with a levelling off thereafter. In 1956, the increase was essentially a linear function of rates of K application. This indicated that a further increase in clover yields was possible with further increases in potassium dressings. The significant PK_{LL} interactions which occurred in 1954 and 1955 indicated that the increase in yields per added increment of potassium tended to increase with increasing levels of phosphorus.

Grass Fraction

Phosphorus fertilization was effective in stimulating the grass production in 1954 and 1955. The linear term was highly significant in both years. Increased yields of timothy were obtained with increasing levels of phosphorus. The yield data showed no trend in 1956.

Potassium fertilization caused a highly significant linear decrease in the timothy yields in 1954. The yields decreased with increasing levels of K. This decrease appeared to be due to the competition of the invigorated clover following potassium dressings. In 1955 and 1956, no such trend took place presumably because the clover stand was much reduced.

Total Production

Phosphorus application significantly increased the clover-grass yields in 1955 only. The grass alone was responsible for this increase as phosphorus did not increase the clover yields. Potassium application exerted a marked effect on the clover-grass yields but it was due to the response of clover alone since potassium had either a depressive or no effect on the grass yields. In 1954, the total production increased linearly until the potassium application reached 120 pounds per acre and then levelled off. In 1955 and 1956, the linear trend was significant; the total production increased with increasing levels of K.

The amounts of clover and timothy harvested per acre differed widely between years. The yield of ladino clover was approximately seven times higher in 1954 than in 1955 or 1956. The fertilizers were applied only at seeding time and the large yields obtained during the first harvest year removed much of the potassium. It has been shown that annual or split annual applications of a potassium salt must be resorted to if the productive life of ladino clover is to be extended and its production maintained at a

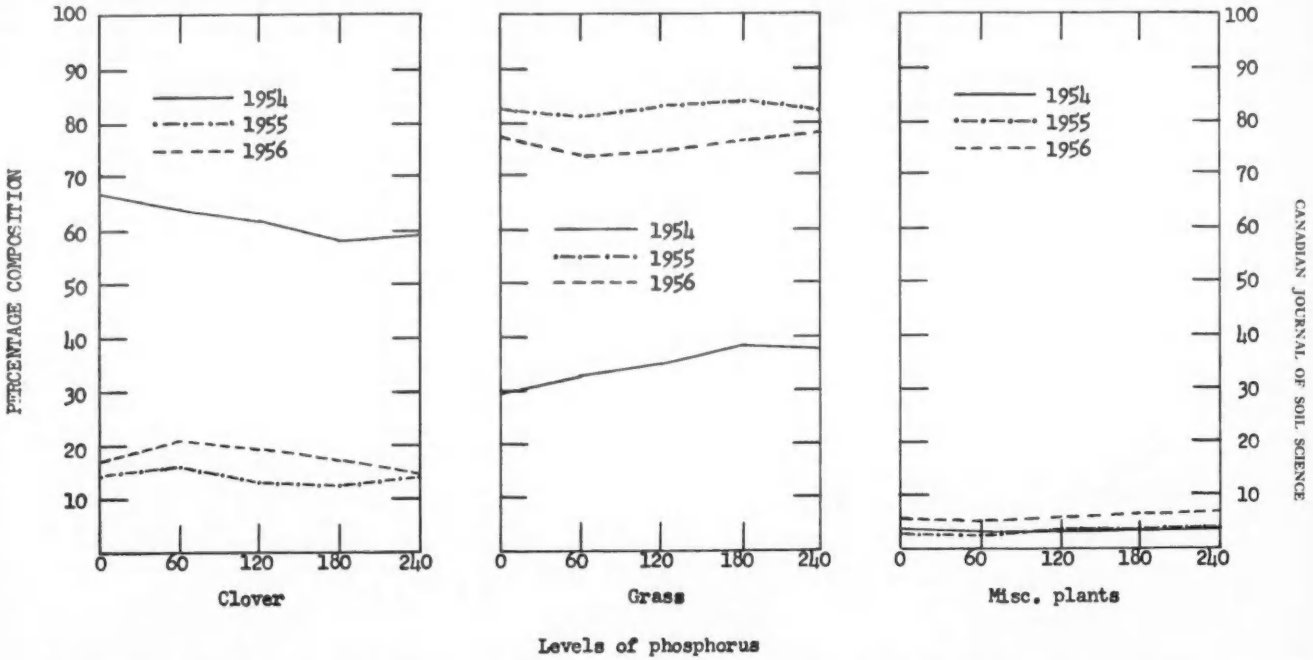

FIGURE 1. Botanical composition of forage harvested in 1954, 1955 and 1956, as influenced by varying levels of phosphorus application.

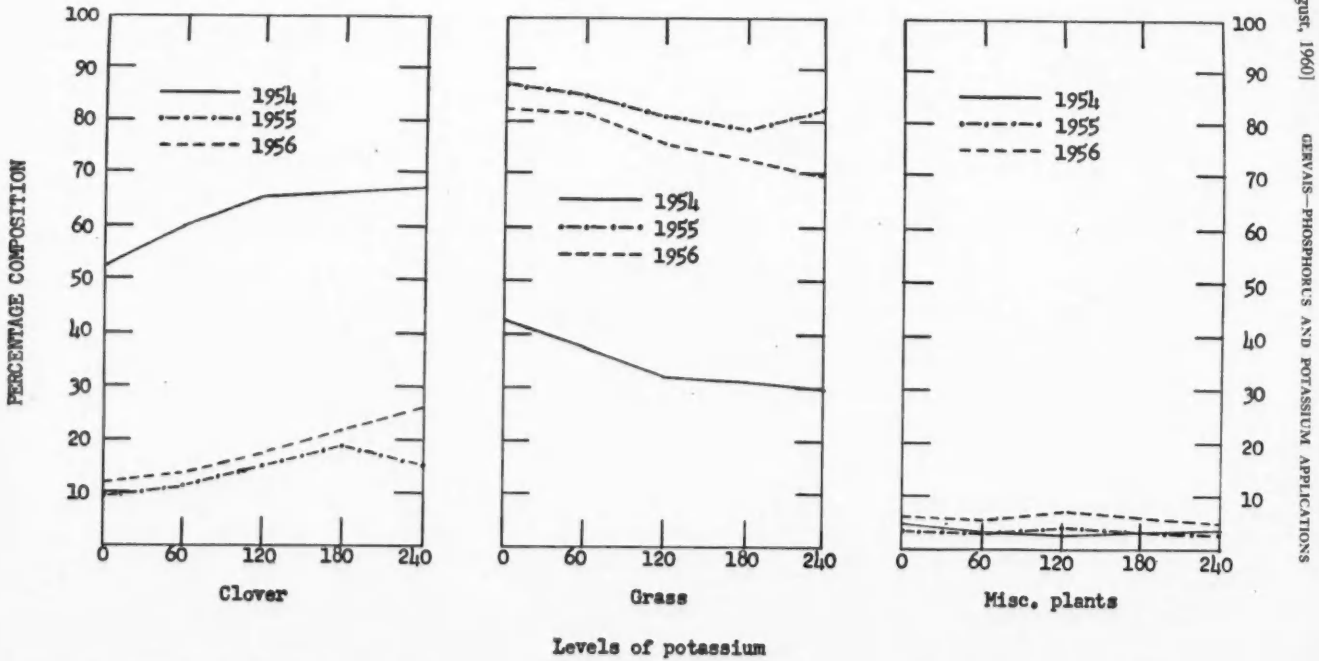

FIGURE 2. Botanical composition of forage harvested in 1954, 1955 and 1956, as influenced by varying levels of potassium application.

TABLE 3. — AVERAGE CHEMICAL COMPOSITION OF LADINO CLOVER AS INFLUENCED BY VARYING LEVELS OF PHOSPHORUS AND POTASSIUM APPLICATIONS 1954-1956

Treatment lb./acre	Percentage							
	Crude protein	Crude fibre	N-free extract	Fat	Ash	Ca	P	K
P_2O_5								
0	26.19	17.30	46.73	1.89	7.89	1.85	0.28	1.33
60	26.98	16.94	46.34	1.89	7.85	1.95	0.30	1.19
120	27.36	17.03	46.01	1.84	7.76	2.01	0.31	1.11
180	27.71	16.53	46.28	1.87	7.61	2.05	0.34	1.03
240	27.89	16.58	45.96	1.88	7.69	2.02	0.35	1.02
K_2O								
0	27.81	16.38	46.54	1.87	7.40	2.05	0.33	0.83
60	27.61	16.79	46.17	1.87	7.56	2.00	0.33	0.93
120	27.24	16.87	46.36	1.87	7.66	1.99	0.31	1.10
180	26.83	17.02	46.27	1.87	8.01	1.95	0.30	1.30
240	26.64	17.31	46.00	1.88	8.17	1.90	0.30	1.52

high level for a number of years (2, 10, 11). Two other factors, slight winterkilling and a severe mid-summer drought, contributed to the reduction in stand in 1955.

The production of grass exhibited a pattern different from that of the clover. Timothy reached its peak production during the second harvest year probably as a result of the much reduced competition from the clover and of nitrogen accumulation in the soil. The drop in grass production during the third harvest year may be the result of a decline in soil fertility.

Botanical Composition of Forage

The botanical composition of the forage harvested in 1954, 1955 and 1956 was based on the yields of dry matter of the clover and timothy fractions and miscellaneous plants. The effects of varying levels of phosphorus and potassium applications on the botanical composition of forage are illustrated in Figures 1 and 2.

A differential response to phosphorus and potassium applications was obtained from the two components of the seeding mixture. There was a general tendency for ladino clover to decrease and for timothy to increase with increasing levels of phosphorus. Potassium, on the other hand, favoured the clover to the detriment of the grass since the percentage of ladino clover in the harvested forage increased and that of timothy declined with successive levels of potassium. The trends exhibited by the clover and the grass following phosphorus and potassium applications were much the same from one year to the next.

Miscellaneous plants were not influenced by varying levels of P and K applications and made a very low contribution during each year. They amounted to only 3.3, 3.1 and 5.9 per cent of the harvested forage in 1954, 1955 and 1956, respectively. A small increase was noted the third harvest year in comparison with the previous 2 years.

Chemical Composition of Forage

The average chemical composition of the clover and timothy fractions for the 3 years as influenced by varying levels of phosphorus and potassium applications is given in Tables 3 and 4. Only the average composition is presented in order to conserve space. The linear and quadratic effects of phosphorus and potassium applications on the chemical composition of each forage fraction are shown in Table 5.

Phosphorus fertilization increased the crude protein content in the clover. Highly significant linear and quadratic effects were obtained; at the higher rates the increments of P were less effective in raising the crude protein content than at the lower rates. Potassium fertilization caused a highly significant linear decrease in the crude protein content in the clover. Neither fertilizing elements altered significantly the percentage of crude protein in timothy.

The percentage of crude fibre in the clover decreased linearly, in general, with increasing levels of phosphorus, whereas the crude fibre content in the grass was not affected. Potassium caused a linear increase in the crude fibre content in both forage fractions.

TABLE 4. — AVERAGE CHEMICAL COMPOSITION OF TIMOTHY AS INFLUENCED BY VARYING LEVELS OF PHOSPHORUS AND POTASSIUM APPLICATIONS 1954-1956

Treatment lb./acre	Percentage							
	Crude protein	Crude fibre	N-free extract	Fat	Ash	Ca	P	K
P_2O_5								
0	16.28	27.17	46.73	2.77	7.05	0.53	0.27	1.96
60	16.01	27.19	47.05	2.81	6.94	0.56	0.28	1.92
120	16.14	27.45	46.60	2.77	7.04	0.57	0.31	1.90
180	16.02	27.21	46.94	2.79	7.04	0.58	0.33	1.88
240	16.12	27.25	46.88	2.79	6.96	0.59	0.33	1.83
K_2O								
0	16.01	26.74	47.82	2.78	6.65	0.60	0.31	1.64
60	16.23	27.09	46.85	2.81	7.02	0.58	0.31	1.79
120	16.22	27.41	46.68	2.77	6.92	0.57	0.30	1.87
180	16.05	27.43	46.57	2.80	7.15	0.55	0.29	2.02
240	16.05	27.60	46.31	2.75	7.29	0.53	0.29	2.18

Species differed in response to fertilization with respect to N-free extract content. Phosphorus was responsible for a linear decrease in N-free extract content in the clover while potassium caused no significant change. With timothy, the opposite response was obtained. Phosphorus showed no effect, whereas a linear decrease was observed as a result of potassium application.

Phosphorus and potassium applications failed to modify the fat content in either forage fractions. Variations were small and no trend was obtained.

Potassium was effective in changing the percentage of ash in the clover and timothy fractions. Highly significant linear trends were obtained. This indicated an increased ash content with increasing levels of potassium. Phosphorus, on the contrary, caused a linear decrease in the ash content in the clover but showed no effect on grass.

The application of potassium resulted in a repressed absorption of calcium by the clover and the grass. The concentration of calcium in the plant tissue was lowered as the rates of potassium application increased. Fertilization with phosphorus gave a response opposite to that of potassium. Phosphorus showed highly significant linear and quadratic effects on the calcium content in the clover. The increases in the calcium content were larger at the lower than at the higher levels of phosphorus. In timothy, the increase in the calcium content was a linear function of rates of phosphorus application.

The phosphorus content in both forage fractions increased linearly with increasing levels of phosphorus fertilizer but decreased linearly with increasing levels of potassium fertilizer.

Application of phosphorus reduced the potassium content in the clover and the grass. With ladino clover, the linear and quadratic terms were highly significant. The decline in potassium content was less at the higher than at the lower levels of phosphorus application. In timothy, the potassium content decreased linearly with increasing levels of phosphorus application. Potassium fertilization, on the contrary, raised markedly the potassium content in the clover and the grass. The uptake of potassium increased with the potassium supply. The highly significant PK_{LL} interaction in the clover fraction indicated that the increase in K content per unit increase in K application tended to decrease with increasing P levels.

During these studies, the percentage of potassium in ladino clover declined from year to year. (Fertilizers were applied at seeding time only). The clover averaged 1.72, 0.97 and 0.72 per cent for the first, second and third harvest years, respectively. Because of high yields and luxury consumption, much potassium was removed during the first harvest year. As a consequence, the average potassium content was reduced by 44 and 58 per cent during the second and third harvest years, respectively. With the exception of few treatments at the two highest levels of potassium application, the clover harvest in 1956 had a potassium content below the critical levels of 0.8 and 0.9 per cent established by Ulric (12) and Chandler *et al.* (5).

The average percentage of potassium in timothy was 2.59, 1.49 and 1.63 for the first, second and third harvest years, respectively. For any

TABLE 5. — LINEAR AND QUADRATIC EFFECTS OF PHOSPHORUS AND POTASSIUM APPLICATIONS ON THE CHEMICAL CONSTITUENTS REPORTED IN TABLES 3 AND 4

	Crude protein	Crude fibre	N-free extract	Fat	Ash	Ca	P	K
Clover fraction								
P_L	**	**	**	—	*	**	**	**
P_Q	**	—	—	—	—	**	—	**
K_L	**	**	—	—	**	**	**	**
K_Q	—	—	—	—	—	—	—	**
PK_{LL}	—	—	—	—	—	—	—	**
Timothy fraction								
P_L	—	—	—	—	—	**	**	**
P_Q	—	—	—	—	—	—	—	—
K_L	—	**	**	—	**	**	**	**
K_Q	—	—	—	—	—	—	—	—
PK_{LL}	—	—	—	—	—	—	—	—

**Significant at 1 per cent point
*Significant at 5 per cent point
–Not significant

one treatment and for each harvest year, the percentage of potassium was consistently higher in timothy than in ladino clover. These data support those of Blaser and Grady (1) who have shown the aggressive potassium competition to ladino clover by grasses. The greater potassium absorptive capacities of the roots of timothy in comparison with those of ladino clover, as pointed out by Drake *et al.* (6), allow the grass to remove more K than the clover. The average potassium content in ladino clover and timothy in the third harvest year was of particular interest. The grass contained more than twice as much potassium as the legume.

In addition to the potassium content, the two components of the forage mixture differed markedly in several other chemical constituents. Ladino clover had higher contents of crude protein and calcium, and lower contents of crude fibre and fat than timothy.

The results of these studies have shown that potassium fertilization is effective in stimulating the growth of ladino clover and that phosphorus fertilization is beneficial to timothy. It appears, however, that even with large initial applications of potassium, a satisfactory stand of ladino clover cannot be maintained for several years. The substantial decrease in the clover stand and production, and in the potassium content of the plant tissue during the second harvest year, suggests more frequent K applications.

ACKNOWLEDGEMENTS

The author is indebted to Dale Smith and J. H. Torrie, University of Wisconsin, for helpful suggestions, guidance and statistical advice; to R. B. Carson, Analytical Chemistry Research Service, Research Branch, Canada Department of Agriculture, Ottawa, for the chemical analyses of the forage; and to A. E. Ouellette and L. Lachance, Research Officers, Experimental Farm, Lennoxville, Quebec, for assistance in carrying out the field work. A scholarship granted by the Quebec Agricultural Research Council to the author during his studies at the University of Wisconsin is gratefully acknowledged.

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FERTILIZER STUDIES WITH WHEAT, OATS AND BARLEY GROWN ON GREY WOODED AND BLACK SOILS IN THE PEACE RIVER REGION OF NORTHWESTERN CANADA

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ABSTRACT

In each of 5 consecutive years, 1951-55, 12 fertilizer treatments were made to wheat, oats and barley grown on fallowed land and on binder stubble land cropped to cereals the previous year. The tests were located on three Grey Wooded soils and one Black soil. Fertilizer response of all three cereals was greater on fallow than on stubble. Phosphate gave much higher yield increases than nitrogen on fallow. Phosphate and nitrogen gave about equal increases on stubble for the Grey Wooded soils but phosphate gave a greater increase on the Black soil. Differences in yield response from nitrogen also occurred amongst the Grey Wooded soils. A few responses were obtained to potash.

INTRODUCTION

Phosphorus has been found to be the primary fertilizer requirement of wheat grown on fallowed land in the Peace River region (1). Mitchell also found that phosphorus gave the largest response for wheat on fallowed land in Saskatchewan (4). In a later paper, Mitchell reported that the effect of fertilizer phosphorus increased fairly rapidly with increments of fertilizer up to about 24 pounds per acre of P_2O_5, but that it levelled off at higher rates (5).

This paper covers a study in which 12 commercial fertilizer treatments were made to grain grown on fallow and binder stubble on three Grey Wooded soils and one Black soil. Fertilizer treatments were made to wheat, oats and barley grown on adjacent areas for each cropping condition. Comparisons were made of differences in yields due to fertilizers, fallow and stubble, crops and soils.

MATERIALS AND METHODS

Wheat, oats and barley were grown after summerfallow and binder stubble. The experiment was conducted over the 5-year period, 1951-55. The locations and soil types of the test areas were as follows:

Baldonnel, B.C. — Codesa sandy loam (Grey Wooded)
Goodfare, Alta. — Donnelly clay loam (Grey Wooded)
McLennan, Alta. — Nampa clay loam (Grey Wooded)
Beaverlodge, Alta. — Landry clay loam (Black).

Twelve fertilizer treatments were made in each test as shown in Figures 1-4. The treatments in each test were arranged in a randomized complete block design with four replicates. At each location, the tests on fallow and binder stubble land were located close to each other to minimize soil differences.

Plots consisted of four rows, spaced 9 inches apart and 1 rod in length. A power V-belt rod-row seeder with disk openers was used for seeding and the fertilizer was placed in the drill row with the seed. Varieties used were Saunders wheat, Olli barley and Beaver oats. Yields were determined by sampling the two centre rows of each plot.

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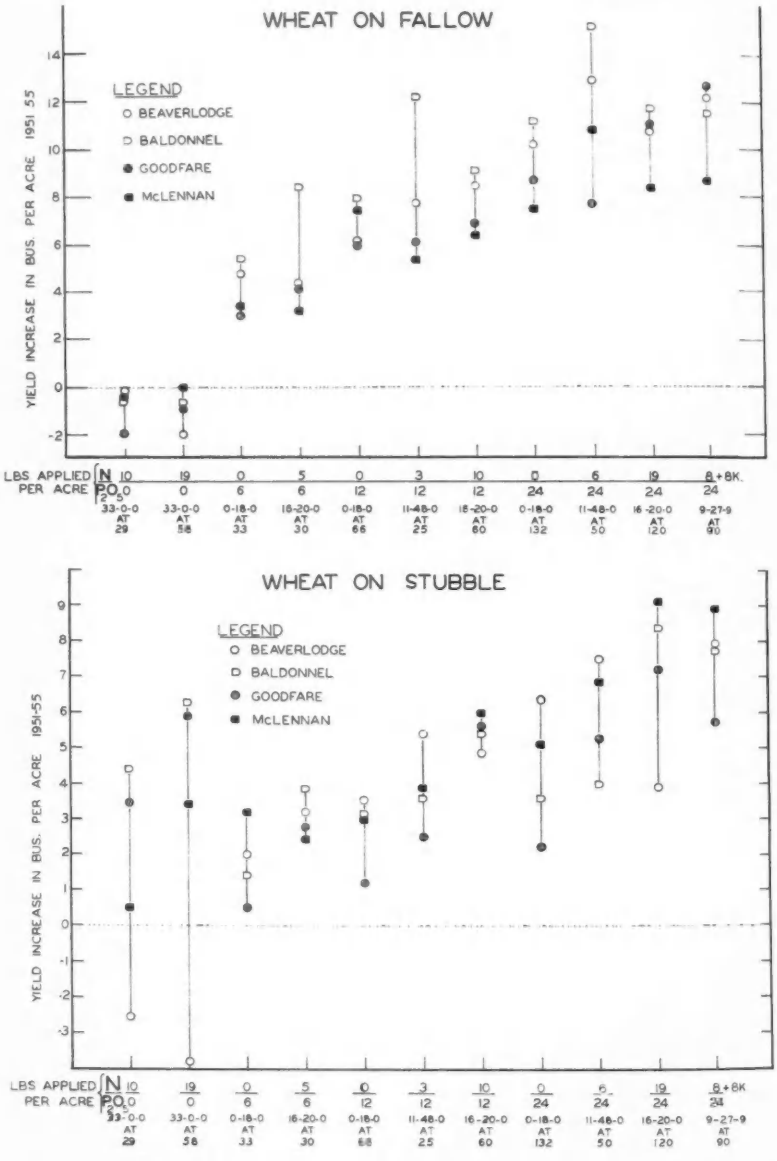

FIGURE 1. Wheat yield increases resulting from fertilizer applications on fallowed and stubble land for four soils, 1951-55. (Yield increases in bu./ac.).

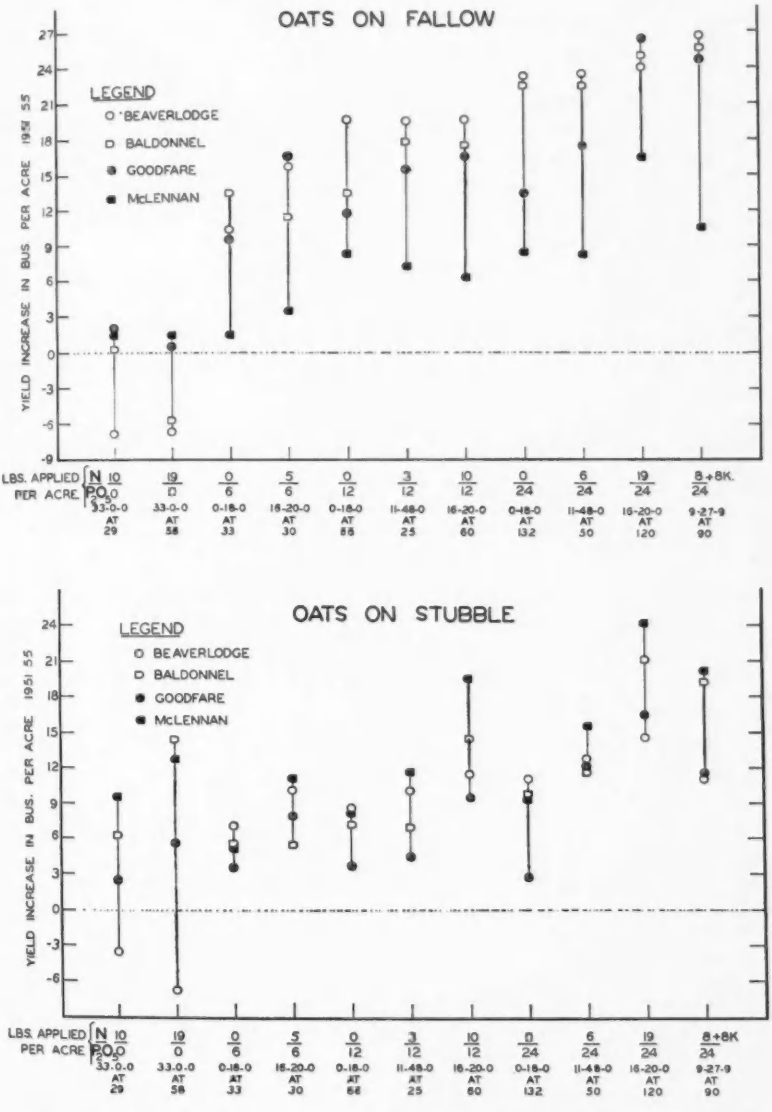
OATS ON FALLOW
LEGEND
BEAVERLODGE
BALDONNEL
GOODFARE
McLENNAN
YIELD INCREASE IN BUS. PER ACRE 1951 55
LBS. APPLIED PER ACRE N P2O5
10 0 33-0-0 AT 29
19 0 33-0-0 AT 58
0 6 0-18-0 AT 33
5 6 16-20-0 AT 30
0 12 0-18-0 AT 66
3 12 11-48-0 AT 25
10 12 16-20-0 AT 60
0 24 0-18-0 AT 132
6 24 11-48-0 AT 50
19 24 16-20-0 AT 120
8+8K 24 9-27-9 AT 90
OATS ON STUBBLE
LEGEND
BEAVERLODGE
BALDONNEL
GOODFARE
McLENNAN
YIELD INCREASE IN BUS. PER ACRE 1951 55
LBS. APPLIED PER ACRE N P2O5
10 0 33-0-0 AT 29
19 0 33-0-0 AT 58
0 6 0-18-0 AT 33
5 6 16-20-0 AT 30
0 12 0-18-0 AT 66
3 12 11-48-0 AT 25
10 12 16-20-0 AT 60
0 24 0-18-0 AT 132
6 24 11-48-0 AT 50
19 24 16-20-0 AT 120
8+8K 24 9-27-9 AT 90

FIGURE 2. Oat yield increases resulting from fertilizer applications on fallowed and stubble land for four soils, 1951-55. (Yield increases in bu./ac.).

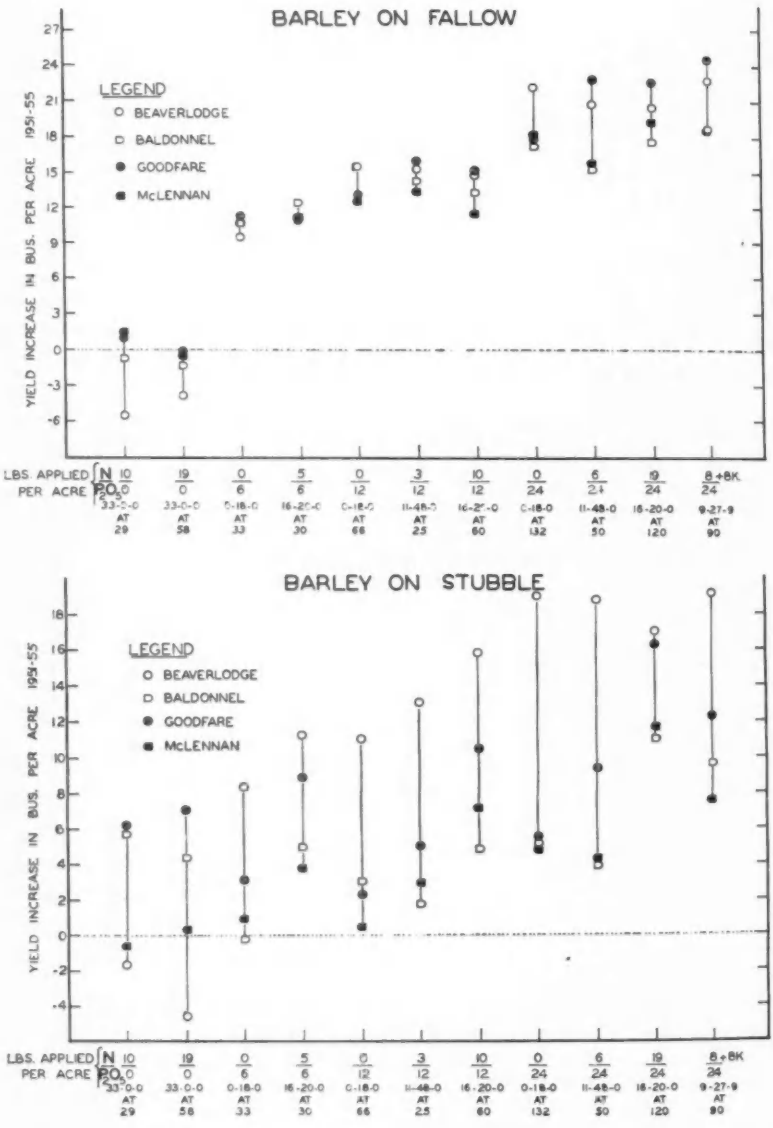

FIGURE 3. Barley yield increases resulting from fertilizer applications on fallowed and stubble land for four soils, 1951-55. (Yield increases in bu./ac.).

Serial analyses (series of experiments) were made for each of the cereals on fallow and on stubble with each of the analyses covering four locations and 5 years. The method of analyses was according to Hayes and Immer (3).

RESULTS

Differences due to Fertilizers

The only statistical differences referred to in the text are those which are significant at the 1 per cent level.

Although differences in yield existed between both years and soils, yield responses to certain fertilizers were sufficiently general that the fertilizer variances when measured against the interaction variances (fertilizer x years and fertilizers x soils) were statistically significant. That is, some of the fertilizers caused consistently greater yield responses for all years and all soils. The detailed account of response to fertilizer is covered under the following headings.

Differences due to Fallow and Stubble

The response to fertilizer for all three cereals was greater on fallow than on stubble for the Grey Wooded soils as shown in Figures 1-3. The unfertilized cereals were also higher yielding on fallow than on stubble for these soils. However, on the Black soil at Beaverlodge, yields obtained on fallow and on stubble were nearly similar. This similarity in yields may have been due to the location of the stubble plots on land more recently broken than the land on which the fallow plots had been located.

On fallowed land, phosphate resulted in much larger yield increases than did nitrogen for all soils. This is illustrated by significant wheat yield increases obtained from the application of phosphate at 6, 12 and 24 pounds per acre over the check. Each increase in rate resulted in yield increases over the preceding rate. However, nitrogen applied at 10 and 19 pounds per acre gave no significant yield increases.

Cereals grown on stubble did not respond as markedly to phosphate as those grown on fallow. For example, phosphate alone applied at 6 pounds per acre to wheat on stubble gave a significant yield increase over the check, but when applied at the 12- and 24-pound rates gave no further significant yield increases over the preceding rates. Nitrogen resulted in pronounced yield increases when the cereals were grown on stubble. For example, the addition of nitrogen at 10 lb./ac. to phosphate at 12 lb./ac. gave a further wheat yield increase on stubble which did not occur on fallow.

The addition of potassium fertilizer resulted in a small yield increase for the cereals grown on stubble as is shown by a comparison N-P-K at 6-24-0 to 8-24-8 in Figure 4. A small increase also occurred for oats and barley on fallow.

Differences due to Crops

Figure 4 gives the yield increase in pounds per acre of the three cereals grown on fallow and stubble. The response to fertilizers on fallow was greatest for barley and about equal for oats and wheat. The responses on stubble were generally greater for barley and oats than for wheat.

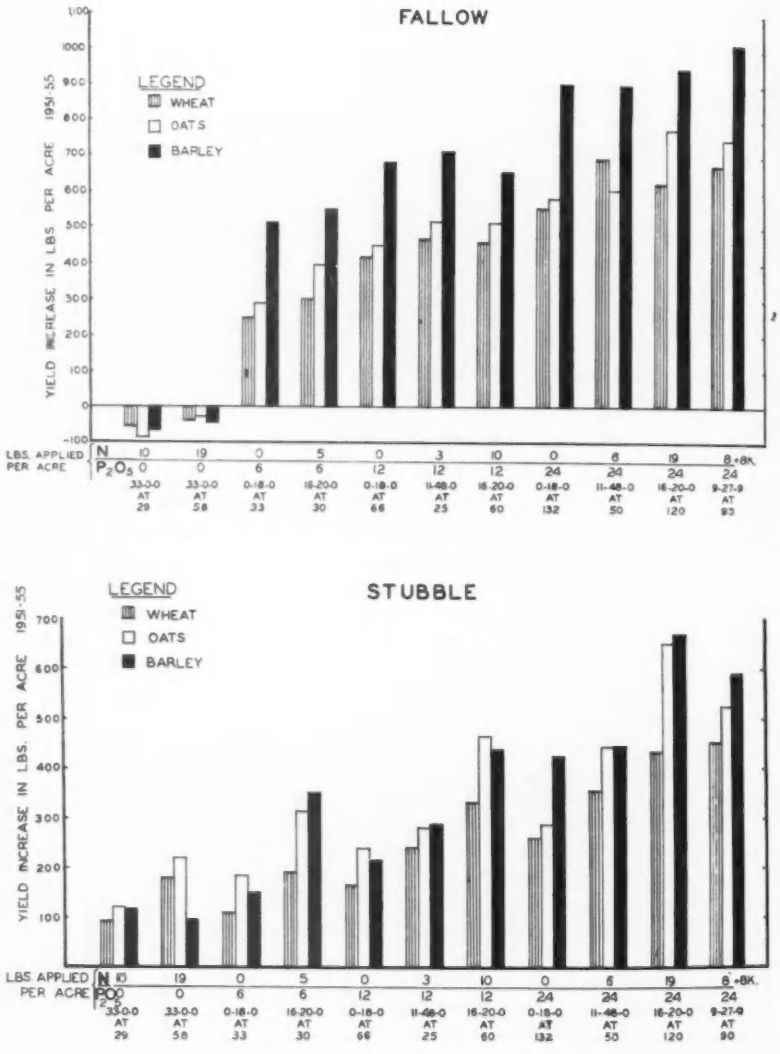

FIGURE 4. Yield increases resulting from fertilizer applications on wheat, oats and barley grown on fallowed and stubble land, basis all soils, 1951-55. (Yield increases in lb./ac.).

Barley responded more to phosphate and less to nitrogen than did wheat and oats. Barley on fallow did not respond to nitrogen additions over phosphate applied alone at 24 lb./ac., whereas a significant yield increase occurred for wheat and oats. Barley grown on stubble showed a greater response from phosphate than did the other cereals. The 24-pound rate gave a significant yield increase over the 12-pound rate; this did not occur for wheat and oats.

Differences due to Soils

All cereals grown on stubble and oats grown on fallow gave a differential fertilizer response to soils.

This differential fertilizer response of the cereals grown on stubble is illustrated by comparing the response of wheat to nitrogen and phosphate. On the Grey Wooded Codesa sandy loam and Donnelly clay loam soils, nitrogen at 10 lb./ac. gave higher yield increases than phosphate at 12 lb./ac., whereas phosphate gave higher yield increases than did nitrogen on Grey Wooded Nampa clay loam. On the Black soil the phosphate application resulted in a yield increase, whereas nitrogen resulted in a decrease in yield.

The differential fertilizer response of oats grown on fallow can also be illustrated by comparing response from nitrogen and phosphate. The yield increase from phosphate at 12 lb./ac. over the increase from nitrogen at 10 lb./ac. on the Black soil was significantly greater than that obtained on the Grey Wooded soils.

DISCUSSION

Unfertilized wheat, oats and barley yielded more on fallowed land than on binder stubble land for the three Grey Wooded soils, Codesa sandy loam, Donnelly clay loam and Nampa clay loam. Also, yield increases from fertilizer were greater on fallow than on stubble. On the Black soil, about the same yields were obtained from identical treatments on fallow and stubble. This may have been the result of a more favourable location of the stubble plots.

Phosphorus fertilizer was primarily responsible for yield increases on fallow for all the soils and on stubble for the Black soil. Response to nitrogen was about equal to that of phosphate for the cereals on stubble on the Grey Wooded soils. It has been found in Saskatchewan that the addition of ammonium nitrate to mono-calcium phosphate increased the availability of fertilizer phosphorus to plants (5, 6). Thus, some of the yield response from the addition of ammonium nitrate to the mono-calcium phosphate in this experiment could have been due to an increased availability of fertilizer phosphorus as well as from addition of nitrogen as a nutrient.

On fallow, barley was more responsive to fertilizer than the other two cereals, whereas on stubble, both barley and oats showed greater responses than wheat. Gingrich and Smith in a study in Kansas (2) found that barley responded mainly to phosphorus fertilizer and that wheat and oats responded to both nitrogen and phosphorus fertilizers. Mitchell (5) reported that barley utilized a greater proportion of phosphorus fertilizer than wheat or oats. Thus, the greater response of barley to fertilizer in this study may have been due to phosphorus.

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EFFECTS OF SAWDUST USED AS A MULCH AND AS A SOIL AMENDMENT ON SOIL TEMPERATURES UNDER IRRIGATED AND UNIRRIGATED CONDITIONS

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ABSTRACT

Soil temperature readings were taken at 7.30 a.m., noon, and 5 p.m. over a 3-year period (2 years without and 1 year with irrigation) at a point 4 inches below the surface of sawdust-mulched, sawdust-incorporated and check plots. The effect of blackened sawdust mulch on soil temperatures was also studied. Marked differences between soil temperatures in the various treatments were found, the greatest being during July when the difference between the average maximum and minimum air temperature was also greatest. Soil temperatures were lower in the sawdust-mulched than in the check plots, except at 7.30 a.m. under irrigation when readings were higher throughout the season in the mulched plot. After August under irrigated conditions and after October without irrigation a reversal took place, and the soil temperatures became higher under the mulch than in the check due to the slower heat loss from the mulched soil. Incorporating sawdust had only a slight effect upon soil temperatures, but blackening the mulch markedly reduced the soil temperature differences between mulched and unmulched treatments.

INTRODUCTION

In horticultural crop production on Vancouver Island, British Columbia, sawdust is used chiefly as a mulch. With crops such as tree fruits, holly and loganberries, the mulch may remain for many years but when used with strawberries or other crops in a rotation it is usually incorporated within 2 or 3 years of application. Sawdust is also incorporated into certain clay soils to improve their physical properties.

Rowe-Dutton (3) made a comprehensive review of world literature up to 1957 on mulching of vegetables. While she reported on the effects of paper mulches on soil temperatures, little information other than that from Saanichton (5, 6), was presented on the effect of sawdust on soil temperatures. Johnson (2) recorded soil temperatures during May and October 1941 and reported that soils with sawdust mulch or incorporation treatments remained more uniform in temperature than soil without sawdust. White (4) recorded soil temperatures hourly in sawdust-mulched and unmulched plots from 5 a.m. to 11 p.m. during one day in August and found that temperatures in the unmulched plots at the 2- and 6-inch depths remained above those in the mulched plots.

This study was undertaken because of the need for more knowledge of the effects of sawdust mulch, and of sawdust when incorporated, on soil temperatures for the period from early spring to late fall. The effect of blackening the sawdust was also studied to see if it would alter the effect of the mulch on soil temperatures.

MATERIALS AND METHODS

Soil temperatures were recorded from 1952 to 1954 in an experiment located on a Tolmie clay loam soil in which vegetables were grown. The treatments laid out in April 1951 were:

(a) 2-inch sawdust mulch, which was maintained by adding sufficient sawdust each spring to bring the depth up to 2 inches.
(b) 1 inch of sawdust incorporated annually 1951-53, and rotovated into the soil to a depth of 8 inches.

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(c) 4 inches of sawdust incorporated in 1951 and rotovated into the soil to a depth of 8 inches.
(d) Check — manure was applied annually at 10 tons per acre and disked into the soil to a depth of 4 inches.

In 1952 two plots adjacent to the experimental area were mulched with 2 inches of sawdust. In order to investigate the effects on soil temperatures of blackening these plots, "breeze", a residue from coke furnaces, was applied thinly to the surface of one plot and mixed throughout the depth of the mulch in the other.

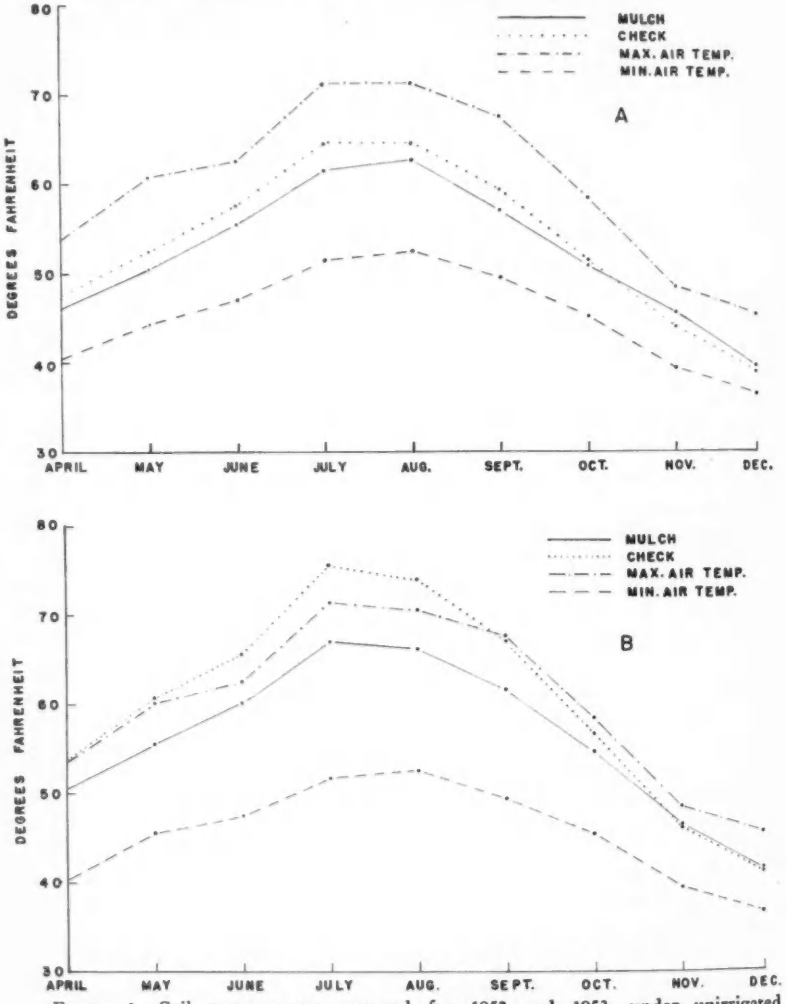

FIGURE 1. Soil temperatures averaged for 1952 and 1953, under unirrigated conditions at A) 7.30 a.m., and B) 5 p.m., in mulch and check plots, and maximum and minimum air temperatures.

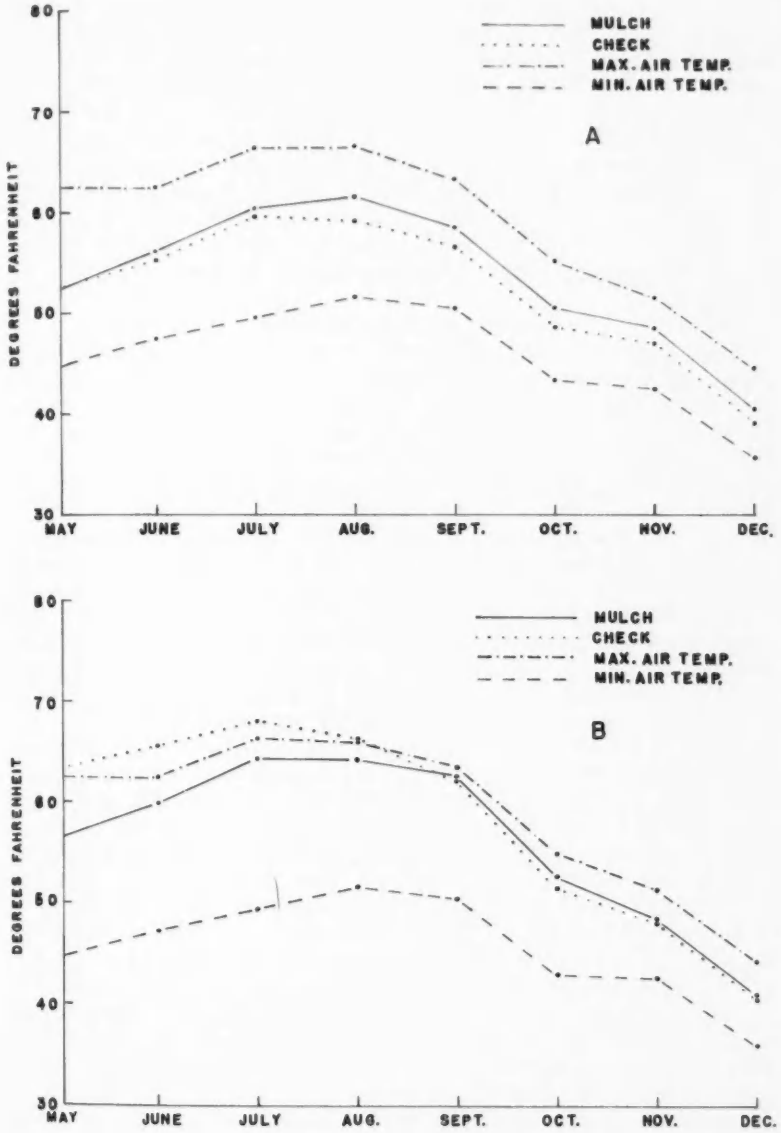

FIGURE 2. Soil temperatures under irrigated conditions at A) 7.30 a.m., and B) 5 p.m., in mulch and check plots and maximum and minimum air temperatures.

The sawdust was a mixture of hemlock and Douglas fir. R-200 "Yel-O-Bak" laboratory thermometers were placed in each plot in a centrally located block of the experiment. As safeguards against breakage and any effect of solar radiation on soil temperature readings, the stems were protected by a U-shaped wooden shield. Temperatures were recorded 4 inches below the soil or sawdust surface three times weekly at 7.30 a.m., noon, and 5 p.m. Daily maximum and minimum air temperatures were measured 4 feet above the soil surface in a standard Stevenson screen (1). All thermometers were calibrated and had 1 degree F. graduations. Monthly mean soil and air temperatures were calculated from the data.

In 1952 and 1953 no irrigation was practised but in 1954 all plots received irrigations by sprinklers according to the need of plants in the driest plots.

RESULTS AND DISCUSSION

Soil temperatures over the 3-year period for the two sawdust-incorporated treatments were similar and slightly higher in the two unirrigated years than under irrigated conditions. The mean seasonal difference between the soil temperatures in these two plots and in the check plot was less than 0.7°F. and, therefore, data on the latter treatment only are presented. Noon readings in mulched and check plots were intermediate in all cases and therefore are not included in the presentation of results.

The averages of soil temperatures for the 1952 and 1953 seasons under unirrigated conditions are presented for the 7.30 a.m. and 5 p.m. readings (Figures 1A and 1B). It may be seen that much higher temperatures occurred in the check than in the mulched plot, particularly at the 5 p.m. readings, the differences being greatest during July, when the differences between the maximum and minimum air temperatures were also greatest. The greatly increased daily rise in the check compared to the mulched plot indicated the marked insulative effect of sawdust under these conditions.

In 1954 when all plots were watered and the soil moisture in the driest plots maintained at a level considered optimum for plant growth, the daily rise in soil temperature in the check plot was again more than in the mulched plot (Figures 2A and 2B) but much less than the 1952-53 average. While part of this effect was due to the lower maximum air temperatures in the cooler summer of 1954, part is attributed to the higher soil moisture content in the irrigated year, as there was a much smaller rise above the maximum air temperature at 5 p.m. A marked difference to the 1952-53 average was also observed in the 1954 soil temperature of the mulched plot at 7.30 a.m. which was above that of the check plot for almost the entire season.

The insulative effect of the sawdust mulch was again demonstrated by the fact that the general trend of soil temperatures at 7.30 a.m. was quite similar under both irrigated and unirrigated conditions, despite the higher maximum air temperature of the latter. On the other hand, temperature of the soil in the check plot fluctuated more widely, with a daily rise to a higher level in the summer of 1952 and 1953, due partly to the greater difference in minimum and maximum temperatures, and partly to more rapid warming of the drier soil.

A reversal in soil temperatures took place late in the season and tem-

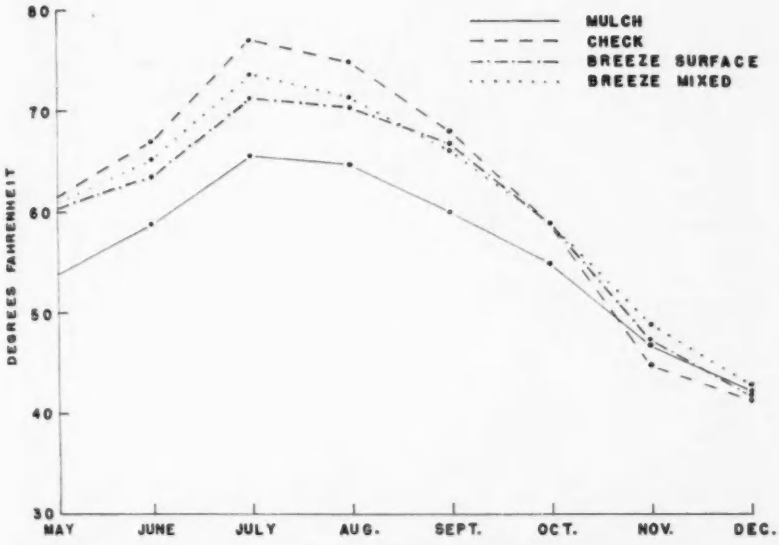

FIGURE 3. Soil temperatures under irrigated conditions at 5 p.m. in sawdust mulch, surface-blackened mulch, mulch blackened throughout, and check plots.

peratures in the mulch plot became warmer than in the check plot, except for the 7.30 a.m. readings under irrigation. Under unirrigated conditions it occurred 14 days later at 5 p.m. than at 7.30 a.m. This temperature reversal again appeared to be due to the insulative effect of the mulch which reduced the rate of heat loss from the soil.

The blackening of the sawdust mulch increased soil temperatures to a marked degree, the "breeze" being more effective when mixed with the mulch than when applied to the surface (Figure 3). The higher soil temperatures from the blackening treatments were marked throughout the season until November when all differences between treatment became small. The data show how the differences between soil temperatures in sawdust-mulched and unmulched plots can be reduced by blackening all the sawdust or, to a somewhat lesser degree, the surface of the mulch.

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SOIL HEAVING IN ALFALFA PLOTS IN RELATION TO SOIL AND AIR TEMPERATURE[1]

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INTRODUCTION

Crop damage due to soil frost heaving may be serious in some areas when snow cover is limited and temperatures fluctuate near the freezing-point. Lamb (5) indicates that 10 per cent of the fall-seeded crop in Ohio has to be ploughed in the spring in some years because of frost-heaving damage, and this may amount to 200,000 acres. Decker and Ronninger (3) record heavy crop losses in Maryland each year and they add that infrequent snow cover aggravates this situation. In Canada, information of soil frost heaving damage to agricultural crops is lacking.

LITERATURE REVIEW

The mechanics of soil frost heaving has been a matter of considerable interest to Taber, who has done much of the pioneer work in this area (7). He stated that frost heaving of soils is caused by the segregation of layers of ice in the soil and is related to (a) size and percentage of voids in the soil; (b) size of soil particles; (c) water content of the soil; (d) rate of cooling; (e) depth of freezing; (f) direction of cooling, and (g) external pressures. Of the above variables, soil moisture content is the most important (2). A monograph by the United States Highway Research Board contains a complete review of the mechanics of soil frost heaving and associated engineering problems (4).

Crop damage, due to soil frost heaving, is not usually the result of a lack of cold resistance of the plant. Winter hardiness is the result of physiological processes within the plant, whereas resistance to soil frost heaving is almost entirely a physical process. Ice and frozen layers of soil "collar" the plant at some point along the root and as the soil volume increases, the plant roots are torn from the soil. Lamb (5) has studied the tensile strength and extensibility of wheat roots and concludes that these factors are important to consider, when the physical forces of frost are imposed on plants. Decker and Ronninger (3) related soil frost heaving to various ground covers and they conclude that Ladino clover, with a relatively shallow root system, was heaved considerably, and consequently damaged, whereas alfalfa, orchard grass, Kentucky blue grass and smooth brome grass were relatively unaffected. Heaving was closely associated with periods of alternating freezing and thawing temperatures.

The purpose of the present study was to design a simple frost "heavometer" and relate soil frost heaving in field plots to snow cover and air and soil temperatures at Ottawa.

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[3]Meteorologist, Plant Research Institute; seconded from Canada Department of Transport to Research Branch, Canada Department of Agriculture, Ottawa, Ont.

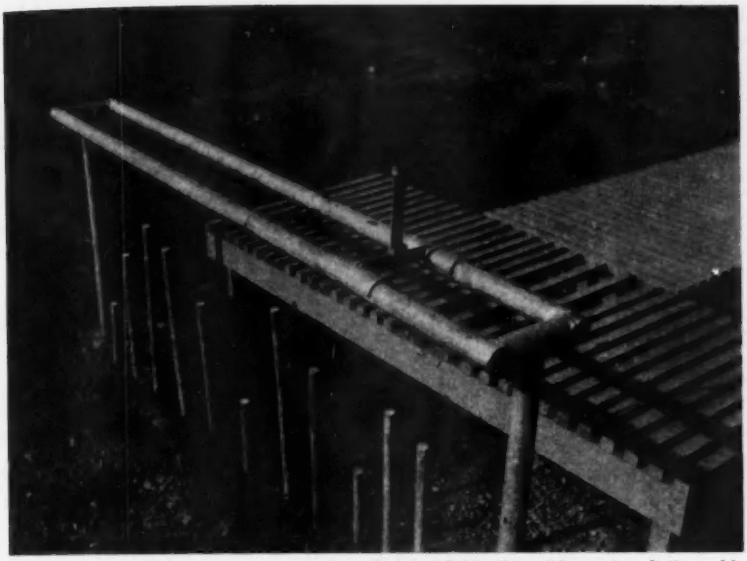

FIGURE 1. Soil frost heavometer installed in field plot. Note the sliding rider, cat-walk, and hardwood dowels.

METHODS AND PROCEDURES

The instrument used to measure soil frost heaving in this study is shown in Figure 1. It consists of two parallel slide bars 5 feet long, fastened 5 inches apart at the ends by a single bar which is mounted at right-angles to the parallel bars. The single bars were sunk 48 inches into the ground (below frost level) so that the parallel bars were held horizontally and approximately 24 inches above the ground. The single, perpendicular bars have a 12-inch flange on the bottom, as added insurance that the instrument will not heave. A rider was placed on the horizontal bars and was constructed to slide freely along the entire length. Hardwood dowels, ¾-inch diameter and sharpened on one end, were driven various depths into the soil directly beneath the horizontal bars. The change in distance between the top of the dowels and the reference point on the rider was taken as the amount of soil frost heaving. The observer approached the installation on a catwalk so that the soil area beneath the instrument remained untrampled. The hardwood (oak) dowels were driven into the ground at 4-, 8- and 12-inch depths in quadruplicate, approximately 2 weeks prior to the first fall frost.

Decker and Ronninger (3), independently devised an instrument similar to the above. Their device was equipped with a micrometer gauge on the rider. In addition, side "wings" on the rider enabled the operator to measure heave of a greater number of dowels or plants. The rider and horizontal bar assembly could be removed from the vertical supports and transferred to a new set of supports in another area for additional measurements.

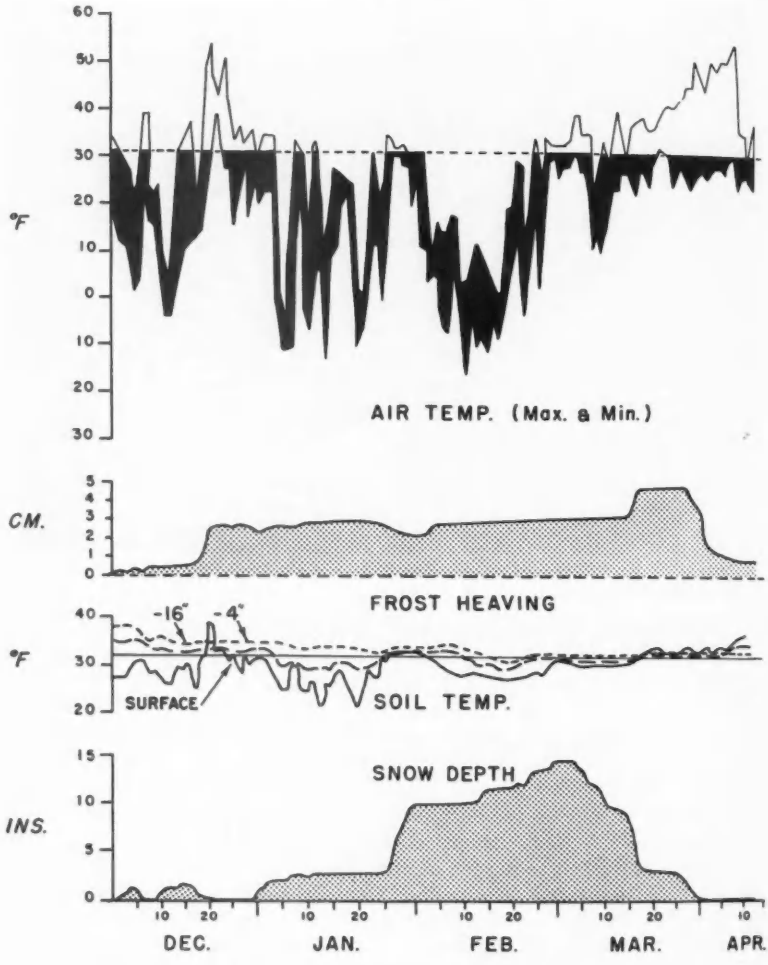

FIGURE 2. Relationship between time of year and air temperature, frost heaving, soil temperature at the surface and 16- and 4-inch depths, and snow depth during the winter 1957-58.

Measurements of soil frost heaving and soil temperatures were measured daily at 8.00 a.m. Measurements of temperatures were made at the surface, and at 4- and 16-inch depths. Air temperature, at 48 inches in a standard Stevenson screen, and snow depth were also measured daily. These observations were made at Ottawa during the winters of 1957-58, and 1958-59. The frost heavometer was installed in an imperfectly drained glacial till soil (Matilda silt loam) seeded to alfalfa at 12 lb./acre each spring.

RESULTS AND DISCUSSION

An analysis of variance of the dowel heaving showed no significant differences between treatment (depths), or replications. Consequently, the average heave of all dowels is shown in Figures 2 and 3. Decker and Ronninger (3) found that the shallow dowels heaved more than those at the 8- or 12-inch depth. The difference in the results obtained in Maryland and Ottawa is explained by the difference in snow cover and soil temperature fluctuations between the locations. During the winter of 1957-58, at Ottawa, the entire soil area in which the dowels rested was frozen and in 1958-59 none of the soil froze. However, in Maryland, a shallow layer of soil was probably frozen so that one part of the stake was in frozen and another in unfrozen soil. This may result in differential dowel heaving in Maryland. The amount of heave of a dowel in this condition would be related to the amount of dowel surface in friction with unfrozen soil.

Winter of 1957-58

This winter was characterized by intermittent, moderate snow cover with periods of thaw and widely fluctuating temperatures. Frost penetrated into the soil to approximately 16 inches in February. (See Figure 2). There were 2769 degree days accumulated below and 425 above the freezing-point, relative to air temperature.

Heaving mainly occurred at two periods in December and March. Both examples were marked by negligible snow cover and widely fluctuating air temperatures. During December, the temperature below 4 inches was above 32°F. but the surface temperature varied above and below 32°F. Because the temperature shown is the 8.00 a.m. reading, the diurnal fluctuation of the soil surface temperature was probably quite marked. From January to mid-March, heaving was moderate and gradual except for a slight subsidence during a thaw the first few days in February. This period from January to March is one of increasing new depth and gradual frost penetration. In March, air temperature began to increase. Around March 15, when the snow cover virtually disappeared and the soil surface temperature began to fluctuate, sharp heaving occurred. Decker *et al.* (3) noted a similar relationship in Maryland under sparse snow cover. Such conditions favour maximum ice segregation and heaving. Observations of alfalfa plants in the spring indicated no damage due to the 5-cm. heave.

Winter of 1958-59

Deep snow cover existed nearly all winter from December to March, and temperatures were consistently low. Approximately 4760 degree days accumulated below and 158 above the freezing-point relative to air temperature. However, the thick layer of snow kept the soil essentially free of frost all winter and the soil surface temperature rarely went below 32°F. (See Figure 3). Slight frost penetration occurred in December but disappeared by mid-January. Figure 3 indicates slight heaving during early December when snow cover was sparse and during late March after snow had virtually disappeared. Such heaving as occurred was probably limited to the diurnal accumulation and disappearance of surface ice. The alfalfa plants were not injured by frost heaving or other winter weather factors.

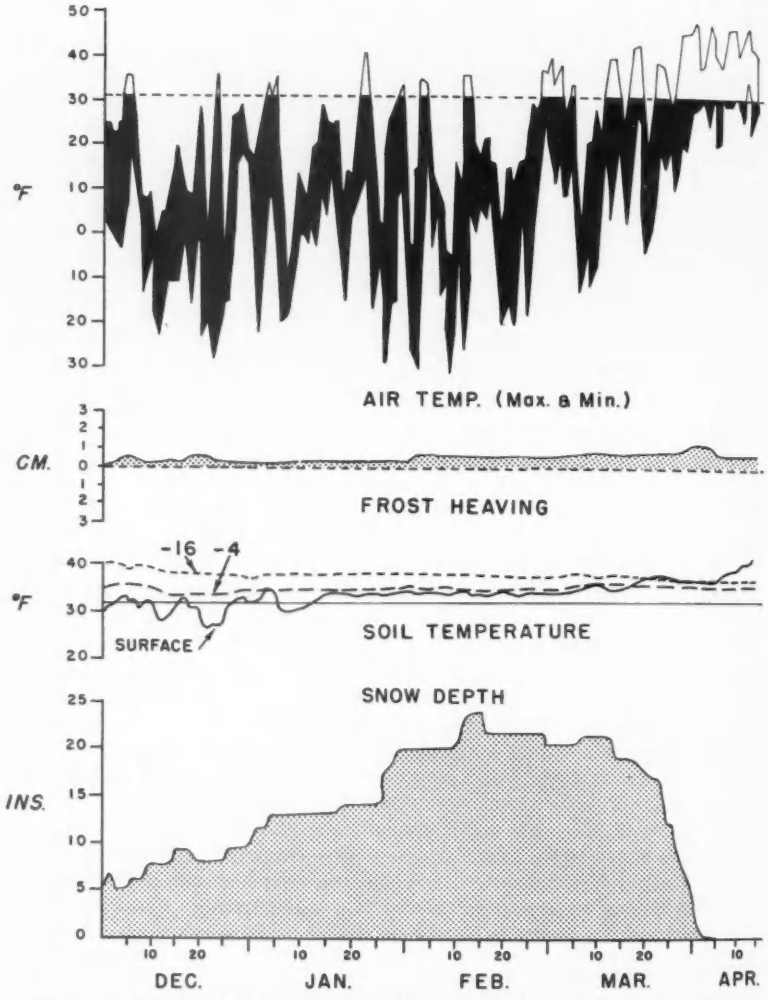

FIGURE 3. Relationship between time of year and air temperature, frost heaving, soil temperature at the surface and 16- and 4-inch depths, and snow depth during the winter of 1958-59.

It is noteworthy that, even though the period from January to mid-March was marked by widely varying minimum temperatures, the soil temperatures were unaffected because of snow cover. During the previous winter, when snow cover was lacking, soil temperature varied with air temperature.

The above data and also that of Decker and Ronninger have shown the usefulness of a frost heavometer in measuring frost heaving in field plots (3).

The above workers in Maryland were able to measure the heave of individual plants and found that this heaving was indicative of the heaving of the wooden dowels. In the Ottawa experiment no attempt was made to follow the heave of individual plants. In another report (1) the authors have described another type of heavometer which rests on the soil surface and therefore indicates changes in the level of the soil surface. It was found that the "dowel" heavometer and the "surface" heavometer indicated heave at the same time although not to the same degree over the period of a winter. However, the dowels were much more sensitive to changes in the weather, whereas the "surface" instrument was quite sluggish and showed much less sensitivity to external conditions. Therefore the dowel instrument was adopted instead of the "surface" heavometer. Also, it was felt that the shape of the dowels more closely resembled a plant root than any other object. Hence the dowel would react to the forces of heave and subsidence in a manner more closely resembling plant roots than any other object. Observations of Decker and Ronninger (3) substantiate this point of view.

Differential heaving of dowels did not occur at Ottawa. As previously suggested, differential heaving of dowels may result from friction along the unfrozen soil-dowel interface. Consequently, a dowel placed 12 inches deep would heave less than one driven 4 inches in the soil, provided only a shallow layer of soil was frozen, since under this condition the heaving forces are located in the first 4 inches of soil. If 12 inches of soil were frozen, then a 12- and 4-inch dowel would probably heave a similar amount since in both cases the entire soil volume in contact with the dowel is frozen.

Such factors as ice lenses under a particular dowel may also enter here. Obviously these relationships may become quite complicated.

The Ottawa and Maryland data suggest that conditions of alternate freezing and thawing are required for frost heaving. Other data have shown that this is not the case*.

However, water *is* necessary before soil can heave. It is generally known that moisture migrates to freezing interfaces, so that periods of alternate freezing and thawing tend to cause the accumulation of water in the surface layers of soil. It is suggested, therefore, that alternate freezing and thawing favour frost heaving in field plots mainly because water accumulates near the surface under these conditions which in turn provides more optimum conditions for soil frost heaving to take place.

SUMMARY

A simple frost heavometer has been described, and data presented which indicate that measurements of soil frost heaving of field plots may be obtained. The data show the protective effect of snow on field plots and strongly support the view that serious heaving in field plots mainly occurs during periods of limited snow cover and fluctuating soil and air temperatures, particularly when variations are near the freezing-point. It is also suggested that conditions of alternate freezing and thawing favour heaving because these conditions also favour the accumulation of water

*Miller, R. D. Dept. of Agronomy, Cornell University, Ithaca, N.Y. *Private communication.* 1960.

near or at the surface. Periods of steady cold under the conditions of this study produced only slight heaving, possibly because of insufficient moisture within the soil profile.

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AN INVESTIGATION OF THE INTERCEPT METHOD FOR DETERMINING THE PROPORTION OF DOLOMITE AND CALCITE IN MIXTURES OF THE TWO

I. Theoretical aspects of the rate of solution of dolomite when a number of crystals are present[1]

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ABSTRACT

The nature of the log V vs. t plot, representing the rate of solution of dolomite consisting of a number of crystals, has been analysed theoretically. The plot may be concave either upwards or downwards, depending on the size distribution of the crystals. Nevertheless, the deviations from linearity, during the time required to dissolve about 50 per cent of the smallest crystal, are always within limits. These limits are calculated and their significance in relation to the line of best fit is discussed.

INTRODUCTION

The intercept method (2), for determining the proportion of dolomite and calcite in mixtures, depends on the marked difference in their rates of solution in an excess of 4 N HCL and on the experimental evidence that the log $(H_\infty - H_t)$ vs. t plot was linear in the early stages of the solution of dolomite. Since $(H_\infty - H_t)$ is proportional to V, the volume of dolomite present at any time (t) during the solution process, $(H_\infty - H_t)$ is replaced with V for convenience in the following treatment. There is no doubt concerning the great difference in their rates of solution. The premise, however, that the log V vs. t plot is linear during any stage of the solution of dolomite does not follow from the fact that the rate of solution, for conditions similar to those used in the intercept method, is proportional to the surface area exposed to the acid (1).

The reported linearity of the log V vs. t plot could arise from either or both of the following reasons: The departure from linearity might be too small to be detected from the graphs, or the experimental error in measuring V might be large enough to mask any deviation from linearity.

It is the purpose here to consider the characteristics of the log V vs. t plot when there are a number of crystals present, assuming the rate of solution is proportional to the surface area exposed to the acid. The investigation is presented in two parts. Part 1 deals with a theoretical analysis of the log V vs. t plot. In Part 2, the conclusions presented in Part 1 are supported by experimental evidence and the intercept method is considered in the light of these results.

THEORY

If the log V vs. t plot is linear during the early stages of solution, the ln V vs. t plot must also be linear and the relation between V and t can be expressed by the equation

$$V = V_o e^{-K_2 t} \qquad (1)$$

the logarithmic form of which is

$$\ln V = \ln V_o - K_2 t \qquad (2)$$

where V_0 is the volume of dolomite at zero time and K_2 is a constant for any one sample. The problem is to show the difference between V as

[1]Contribution No. 6, Soil Research Institute, Canada Department of Agriculture, Ottawa, Ont.

expressed by equation (1) and the V calculated on the basis that the rate of solution is proportional to the surface area exposed to the acid.

It was shown by Ferrari and Sessa (1) that the rate of solution of a single crystal of dolomite was expressed by the differential equation.

$$-\frac{dV_1}{dt} = hS \tag{3}$$

where S is the surface area of the crystal at time (t), h is a rate constant, and the subscript 1 denotes a single crystal. The solution of equation (3) given by Ferrari and Sessa was

$$V_1^{1/3} = V_{o1}^{1/3} - \frac{kht}{3} \tag{4}$$

where k is defined by the relation

$$S = kV_1^{2/3}$$

Equation (4) is a solution of equation (3) if the crystal is symmetrical in shape. If the crystal is not symmetrical, k is a function of time and the solution of (3) depends on the relation between k and t. Ferrari and Sessa showed, however, that equation (4) represented the rate of solution of single crystals of dolomite satisfactorily even though the crystals were not symmetrical. This is not surprising since it can be shown that, except in extreme cases, k is essentially constant while most of the crystal dissolves. Calculations of theoretical values of V as a function of time are, therefore, based on equation (4) and, for the sake of convenience, it is assumed that the crystals are cubes. Any other symmetrical shape could be used but cubes are a good approximation to the actual shape of the crystals in a ground sample of dolomite.

When both sides of equation (4) are cubed it becomes

$$V_1 = V_{o1} - khtV_{o1}^{2/3} + \frac{k^2h^2t^2V_{o1}^{1/3}}{3} - \frac{k^3h^3t^3}{27} \tag{5}$$

If the sample contains a number of crystals, equation (5) applies to each crystal and the equation for such a sample is obtained by summing the individual equations to give

$$\sum_1^m V_j = \sum_1^m V_{oj} - kht \sum_1^m V_{oj}^{2/3} + \frac{k^2h^2t^2 \sum_1^m V_{oj}^{1/3}}{3} - \frac{k^3h^3t^3m}{27} \tag{6}$$

where the subscript j refers to the j th crystal and m is the number of crystals present. $\sum_1^m V_j$ and $\sum_1^m V_{oj}$ are equal to V and V_o respectively, consequently equation (6) can be written

$$V = V_o - kht \sum_1^m V_{oj}^{2/3} + \frac{k^2h^2t^2 \sum_1^m V_{oj}^{1/3}}{3} - \frac{k^3h^3t^3m}{27} \tag{6a}$$

It is easier to compare V represented by equation (6a) with V represented by equation (1) when the summations are expressed in terms of the length of the sides of the crystals. To do this the following symbols are used to represent conditions at zero time,

α_i: The fraction of V_o represented by the i th crystal size.

ax_i: The length of the side of the i th crystal size, where a is the length of the smallest crystal.

m_i: The number of crystals of the i th crystal size.

It can be shown that

$$m_i = \frac{\alpha_i V_o}{a^3 x_i^3}$$

$$m = \frac{V_o \sum_1^n (\alpha_i/x_i^3)}{a^3}$$

$$\sum_1^n V_{oi}^{2/3} = \frac{V_o \sum_1^n (\alpha_i/x_i)}{a}$$

$$\sum_1^n V_{oi}^{1/3} = \frac{V_o \sum_1^n (\alpha_i/x_i^2)}{a^2}$$

where n is the number of crystal sizes represented in the sample. With these symbols equation (6a) can be put in the form

$$V = V_o \left[1 - Kt \sum_1^n (\alpha_i/x_i) + \frac{K^2t^2 \sum_1^n (\alpha_i/x_i^2)}{3} - \frac{K^3t^3 \sum_1^n (\alpha_i/x_i^3)}{27} \right] \tag{7}$$

where

$$K = \frac{kh}{a}$$

This equation may also be written

$$V = V_o \left[1 - K_2t + \frac{K_2^2t^2 \sum_1^n (\alpha_i/x_i^2)}{3\left[\sum_1^n (\alpha_i/x_i)\right]^2} - \frac{K_2^3t^3 \sum_1^n (\alpha_i/x_i^3)}{27\left[\sum_1^n (\alpha_i/x_i)\right]^3} \right] \tag{8}$$

where

$$K_2 = K \sum_1^n (\alpha_i/x_i)$$

It should be noted that K_2 has the dimensions of reciprocal time, the same as K_2 in equation (1). It will be assumed for the time being that the K_2's are identical in the two equations. Equations (7) and (8) express the relation between V and t until the smallest crystals are dissolved. They are entirely general and will therefore be used to show the difference between V expressed by equation (1) and the theoretical V.

The difference in the values of V expressed by the two equations (1) and (8) can be seen qualitatively by writing equation (1) with e^{-K_2t} in its expanded form, i.e.

$$V = V_o\left[1 - K_2t + \frac{K_2^2t^2}{2} - \frac{K_2^3t^3}{3!} + \ldots\ldots - \frac{K_2^yt^y}{y!} + \ldots\ldots\right] \quad (9)$$

The first two terms enclosed in brackets are the same in the two equations and the third and fourth differ only in the coefficients of $K_2^2t^2$ and $K_2^3t^3$. This shows that the difference between the two is zero at zero time and is a function of t for any time greater than zero. To express this mathematically, equation (8) is written in the form

$$V = V_oe^{-K2t} + V_o(X - e^{-K2t}) \quad (10)$$

where X is the part of equation (8) enclosed in brackets. The logarithmic form of equation (10) can be written

$$\ln(V - V_oF) = \ln V_o - K_2t \quad (11)$$

where F is the part of equation (10) enclosed in brackets. V_oF is the difference, mentioned above, between the V's expressed by the two equations (1) and (8). The problem is thus reduced to considering possible values of V_oF.

For any particular sample, K_2 and V_o are constants and V_oF is a function of t only. In general, however, V_oF is a function of a, V_o, kh and size distribution as well as t. It is convenient to use Kt, which includes all the variables except V_o and size distribution, as one variable. This reduces the problem to one of three variables, Kt, V_oF and size distribution. The effect of the individual variables can be considered later.

Advantages gained from using Kt as the time variable can be seen from the following considerations. When the symbols used in equation (7) are applied to equation (5) it can be written

$$V_1 = V_{o1}\left(1 - Kt + \frac{K^2t^2}{3} - \frac{K^3t^3}{27}\right) \quad (12)$$

or

$$qV_1 = qV_{o1}\left(1 - Kt + \frac{K^2t^2}{3} - \frac{K^3t^3}{27}\right) \quad (12a)$$

when there are q crystals of the same size. Because equation (12) applies to any crystal in the sample, the fraction of the total initial volume of the smallest crystals, remaining at any stage of the reaction, is equal to the value of the part enclosed in brackets in the equation. Equations (7) and (8) are valid, therefore, in the interval $O<Kt<3$ and values for V_oF can be considered for this interval only. For practical reasons however it is not necessary to consider V_oF for values of Kt greater than 1, which is equivalent to the time when the volume of the smallest crystal is about 30 per cent of its initial volume. It will now be shown that there are maximum negative and positive values for V_oF in the interval $O<Kt<1$.

Negative Values of V_oF

It can be shown

(Appendix 1) that $\frac{\sum_1^n (\alpha i/xi^2)}{\sum_1^n (\alpha i/x_i)^2}$ and $\frac{\sum_1^n (\alpha i/xi^3)}{\sum_1^n (\alpha i/x_i)^3}$ in equation (8)

are equal to one when n equals one and greater than one when n is greater than one. With n equal to one there is only one crystal size present and equation (8) becomes

$$V = V_o\left(1 - K_2t + \frac{K_2^2t^2}{3} - \frac{K_2^3t^3}{27}\right) \tag{13}$$

and K_2 in this case has the same value as K. This shows that the minimum values for the coefficients of $K_2^2t^2$ and $K_2^3t^3$ occur when only one crystal size is present in the sample. It follows that in the interval during which the magnitude of $_e{-}K_2t$ is dominated by the first three terms in its expansion (K_2t small) the greatest possible values of $-V_oF$ occur when there is only one crystal size present. There does not seem to be a simple mathematical proof that this is true in the whole interval $O<Kt<1$.

Although the value of $-V_oF$ decreases as the coefficient of $K_2^2t^2$ increases, it increases as the coefficient of $K_2^3t^3$ increases. It is a fact that there are size distributions which cause the coefficient $K_2^3t^3$ to be very large but in such cases the coefficient of $K_2^2t^2$ is also very large and, even more important, the value of $\Sigma(\alpha\, i/x_i)$ is very small. The latter causes the value of K_2t to be very small because it is Kt multiplied by $\Sigma(\alpha\, i/x_i)$. This reasoning applied to graphical studies of models representing extreme cases of size distribution showed that $-V_oF$ is greatest at any value of Kt from 0 to 1 when there is only one crystal size present.

Furthermore, the second derivative of ln V with respect to Kt for equation (13) is negative for all values of Kt between 0 and 3, which shows that the ln V vs. Kt plot is concave downward. Since the straight line expressed by equation (1) has the same slope as the curve expressed by equation (8) when t equals zero, the value of $-V_oF$ must increase continuously as Kt increases.

Positive Values of V_oF

When there are crystals in the sample larger than the smallest, the coefficients of $K_2^2t^2$ and $K_2^3t^3$ are respectively larger than they are in equation (13). Consequently V_oF will be less negative at each value of Kt than if only one crystal size is present and in fact may be positive. It will now be shown that there is a particular size distribution which causes the greatest possible positive values of V_oF. The expression for F may be written

$$F = 1 - Kt\sum_1^n (\alpha_i/x_i) + \frac{K^2t^2\sum_1^n (\alpha_i/x_i^2)}{3} - \frac{K^3t^3\sum_1^n (\alpha_i/x_i^3)}{27} - e^{-Kt\sum_1^n (\alpha_i/x_i)} \tag{14}$$

It can be shown (Appendix 2) that the maximum value of F, F_m, in terms of Kt and A (the ratio of the largest to the smallest crystal present) occurs when the sample consists of the two crystal sizes only and the fraction of V_o represented by the smallest crystal size is

$$\alpha_1 = -\frac{1}{A-1} - \frac{A}{Kt\,(A-1)} \ln\left[1 - \frac{Kt\,(A+1)}{3A} + \frac{K^2t^2\,(A^2+A+1)}{27A^2}\right] \quad (15)$$

Furthermore, F_m increases continuously as A increases (Appendix 3). The greatest value of F_m, F_m', in terms of Kt occurs therefore when

$$\alpha_1 = -\frac{1}{Kt} \ln\left[1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right] \quad (16)$$

With this value for α_1, F_m' is expressed by the equation

$$F'_m = \frac{Kt}{3} - \frac{K^2t^2}{27} + \left(1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right) \ln\left(1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right) \quad (17)$$

It is obvious from equation (17) that F_m' is zero when Kt is zero and it can be shown (Appendix 4) that it increases continuously as Kt increases from zero to one. Consequently the greatest possible value of V_oF for Kt less than one can be calculated. Furthermore, with A sufficiently large the relation between V and Kt for a given sample is expressed, for all practical purposes, by the equation

$$V = V_o\left(1 - Kt\alpha_1 + \frac{K^2t^2\alpha_1}{3} - \frac{K^3t^3\alpha_1}{27}\right) \quad (18)$$

The second derivative of ln V with respect of Kt for this equation is positive in the whole interval $O<Kt<3$, therefore the ln V vs. Kt plot is concave upwards in this interval. It follows that there is a size distribution which corresponds to a maximum positive value for V_oF for any value of Kt and that V_oF will be smaller for all smaller values of Kt for that particular sample.

DISCUSSION

It has been shown here that the ln V vs. Kt plot may be either concave upwards or concave downwards during the time required to dissolve roughly 70 per cent of the total volume of the smallest crystals in the sample. But there are limits to the departure from linearity in either direction. In other words, regardless of the size distribution, no sample will have a ln vs. Kt plot that deviates from a straight line with slope equal to $\Sigma(\alpha_1/x_1)$ by more than an amount that can be calculated for any value of Kt less than 1. The maximum values of F both positive and negative, shown in Figure 1, when multiplied by V_o are the limits at each value of Kt from zero to 0.6.

It must be realized that in practice the deviations from linearity will be less than the greatest possible value of V_oF at the highest Kt considered. As shown in Figure 1, the greatest possible deviations approach zero as Kt approaches zero. This is because the slope of the straight line considered in the theoretical analysis is equal to the slope of the ln V vs. Kt plot as Kt approaches zero. The straight line of best fit, however, is affected

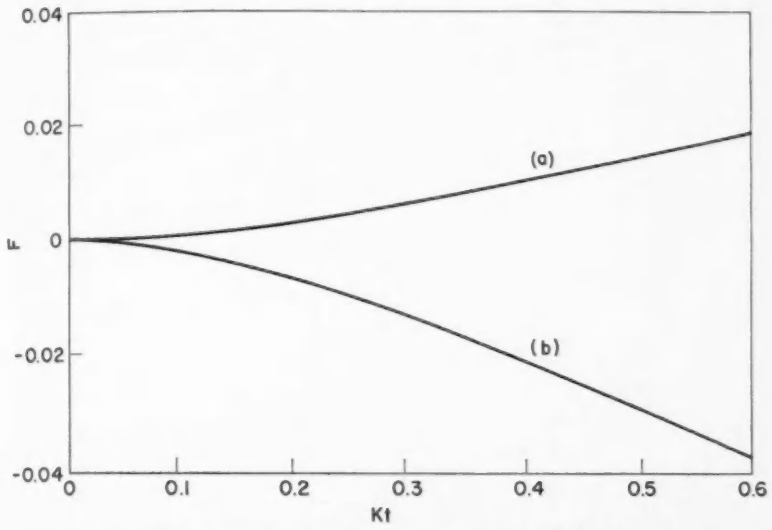

FIGURE 1. Greatest possible positive and negative values of F. (a) positive values; (b) negative values. The positive values were calculated by combining equations (11) and (13). The negative values were calculated by combining equations (11), (16) and (18).

equally by all points in the interval up to the greatest value of Kt considered. Consequently, the greatest deviations from the line of best fit will be less than the limit at a given Kt indicated in Figure 1. This is illustrated in Figure 2 for values of Kt up to 0.6. Curve (b) in the upper part of the Figure represents the model which causes maximum negative values of F. The solid line is the one used in the theoretical analysis and the broken line, below it, is the line of best fit. Curve (c) in the lower part of the figure represents the model which causes maximum positive deviations. In this case the broken line is above the solid line. Curve (a) in the upper part represents a sample intermediate between the two extremes and the two straight lines coincide. In all three cases, the deviations from the line of best fit are considerably less than those indicated by the F's in Figure 1. There does not seem to be any way to calculate the greatest possible deviations from the line of best fit but it should be obvious from this discussion that it will be less than plus or minus one-half the V_oF, indicated by Figure 1, for the greatest Kt considered.

In the analysis so far, the ln V vs. Kt plot has been considered. In practice it is the ln V vs. t, or more generally the log V vs. t plot which is used. Equation (11) can be written

$$\log (V - V_oF) = \log V_o - 0.43\ Kt \sum_1^n (\alpha_i/x_i)$$

which shows that everything concerning V_oF applies to the log plot as well as to the ln plot, the only difference being in the slope of the plot.

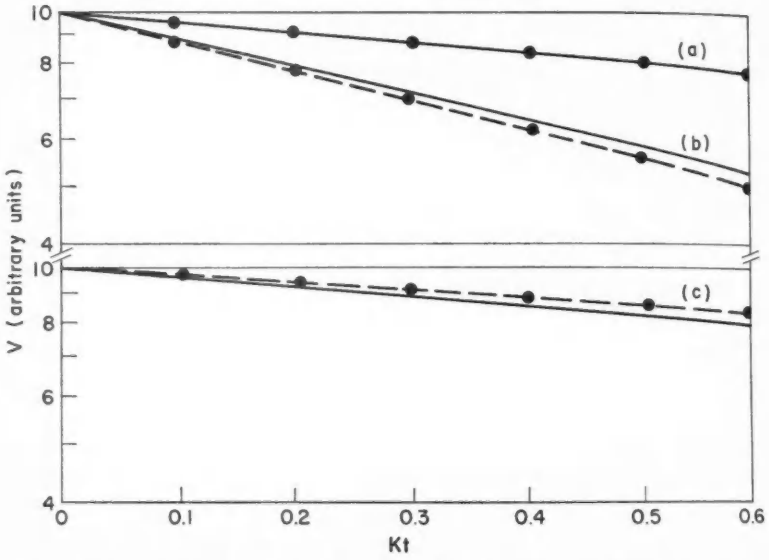

FIGURE 2. Theoretical ln V vs. Kt plots. The slopes of the solid lines are equal to the plots at zero time. The broken lines represent the straight lines of best fit through a number of theoretical points. (a) a model intermediate between the ones that cause the greatest possible positive and negative deviations from the solid line; (b) the model which causes the greatest possible negative deviations from the solid line; (c) the model which causes the greatest possible positive deviation from the solid line.

Furthermore, K is constant for any particular sample so that all conclusions are essentially the same whether Kt or t is used as the time variable.

The value of t corresponding to any Kt can be calculated providing kh and *a* are known. The magnitude of *a* depends on the particular sample used but kh should be essentially the same for all samples of dolomite. The value of kh and the application of this theoretical analysis to the intercept method are dealt with in Part 2.

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2. Skinner, S. I. M., R. L. Halstead, and J. E. Brydon. Quantitative manometric determination of calcite and dolomite in soils and limestones. Can. J. Soil Sci. 39:197-204. 1959.

Appendix 1

The quotients $\dfrac{\sum_1^n (a_i/x_i^2)}{\left[\sum_1^n (a_i/x_i)\right]^2}$ and $\dfrac{\sum_1^n (a_i/x_i^3)}{\left[\sum_1^n (a_i/x_i)\right]^3}$ are equal to one when n is one and greater than one when n is greater than one.

Conditions:

$$\sum_1^n a_i = 1$$

$$x_i = 1$$

$$\frac{x_{i+1}}{x_i} > 1$$

$n \geq 1$ and n is an integer

a_i's and x_i's are real and positive

Proof:

When n is equal to one each summation is equal to one, therefore the quotients are equal to one.

When n is greater than one, let

$$G = \frac{\sum_1^n (a_i/x_i^u)}{\left[\sum_1^n (a_i/x_i)\right]^u}$$

where u is greater than one and can therefore represent either 2 or 3.

The partial derivative of G with respect to x_n is positive. Therefore, G decreases as x_n decreases. When x_n is equal to x_{n-1} there are only $n - 1$ terms. This can be repeated for all x_i's to x_1. Therefore G is greater than 1 when n is greater than 1.

Appendix 2

Find the maximum value of F in the equation

$$F = 1 - Kt \sum_{1}^{n} (a_i/x_i) + \frac{K^2t^2 \sum_{1}^{n} (a_i/x_i^2)}{3} - \frac{K^3t^3 \sum_{1}^{n} (a_i/x_i^3)}{27} - e^{- Kt \sum_{1}^{n} (a_i/x_i)}$$

Arrange all summations so that $(x_{i+1})/x_i$ is greater than 1. Then x_1 is equal to 1 and x_n is the ratio of the largest crystal to the smallest. The following symbols are used

$$A = x_n$$

$$b_i = \frac{A}{x_i} \qquad 1 < b_i < A$$

$$C_1 = \frac{\sum_{2}^{n-1} (a_i b_i)}{A}$$

$$C_2 = \frac{\sum_{2}^{n-1} (a_i b_i^2)}{A^2}$$

$$C_3 = \frac{\sum_{2}^{n-1} (a_i b_i^3)}{A^3}$$

$$C_4 = \sum_{2}^{n-1} a_i$$

Substitute these values into the expression for F and differentiate with respect to a_1 with everything held constant except a_1 and a_n. The result is

$$\frac{\partial F}{\partial a_1} = -\frac{Kt(A-1)}{A} + \frac{K^2t^2(A^2-1)}{3A^2} - \frac{K^3t^3(A^3-1)}{27A^3} + \frac{Kt(A-1)}{A} e^{-Kt\left(a_1 + C_1 + \frac{1-a_1-C_4}{A}\right)}$$

Put the right hand side equal to zero and solve for a_1.

$$a_1 = -\frac{AC_1}{A-1} + \frac{C_4}{A-1} - \frac{1}{A-1} - \frac{A}{Kt(A-1)} \ln\left[1 - \frac{Kt(A+1)}{3A} + \frac{K^2t^2(A^2+A+1)}{27A^2}\right]$$

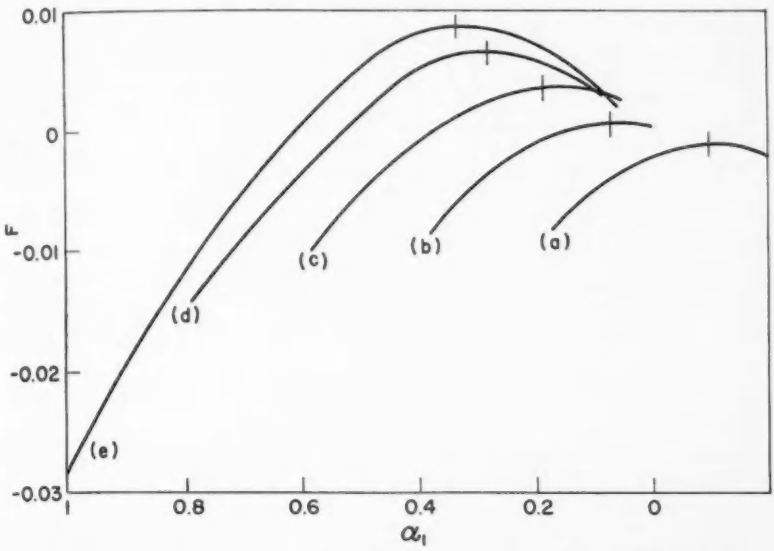
When this value for a_1 is substituted into the expression for F, it gives a maximum F which is denoted F_{max}. The partial derivative of F_{max} with respect to a_{n-1} with everything held constant except a_{n-1} and a_n reduces to

$$-\frac{\partial F_{max}}{\partial a_{n-1}} = \frac{K^2t^2(b_{n-1})(A - b_{n-1})}{3A^2}\left[1 - \frac{Kt(A + b_{n-1} + 1)}{9A}\right]$$

The right-hand side of the equation is positive for all values of Kt less than 3 regardless of the value of A. Therefore, F_{max} will be greatest when a_{n-1} is zero. This can be repeated with all a_i's from a_{n-2} to a_2 inclusive. The greatest value of F_{max}, F_m, in terms of Kt and A in the interval $0 < Kt < 1$ occurs therefore when C_1, C_2, C_3 and C_4 are equal to zero, i.e. when

$$a_1 = -\frac{1}{A-1} - \frac{A}{Kt(A-1)}\left[1 - \frac{Kt(A-1)}{3A} + \frac{K^2t^2(A^2+A+1)}{27A^2}\right]$$

and there are no crystal sizes between the smallest and the largest.



Figure—Appendix 2. Effect on F of the presence of crystal sizes intermediate between the largest and smallest when α_1 is varied, with Kt equal to 0.5. The vertical lines show the greatest possible positive values of F as the number of sizes is decreased from 10 to 2. Maximum number of sizes is 10, A equals 10, b_i equals 11-i, and α_2 to α_9 inclusive are each equal to 0.1 unless otherwise specified. (a) all 10 crystal sizes represented; (b) α_2 and α_3 equal to zero; (c) α_2 to α_5 inclusive equal to zero. (d) α_2 to α_7 equal to zero. (e) α_2 to α_9 inclusive equal to zero.

This is illustrated by an example in the Figure-Appendix 2. It will be noted in the Figure that the maximum does not occur in some cases (curve a) until α_1 becomes negative. Even though it is impossible to have a negative fraction of V_o represented by the smallest crystal size, this does not alter the fact that the maximum increases as the number of sizes between the largest and smallest is decreased, as shown by the five curves.

Appendix 3

Statement:

F_m in the following equation increases continuously with increasing values of A greater than 1 in the interval $O < Kt < 1$.

$$F_m = 1 - \frac{K^2t^2}{3A} + \frac{K^3t^3(A+1)}{27A^2} + B \ln B - B$$

where

$$B = 1 - \frac{Kt(A+1)}{3A} + \frac{K^2t^2(A^2+A+1)}{27A^2}$$

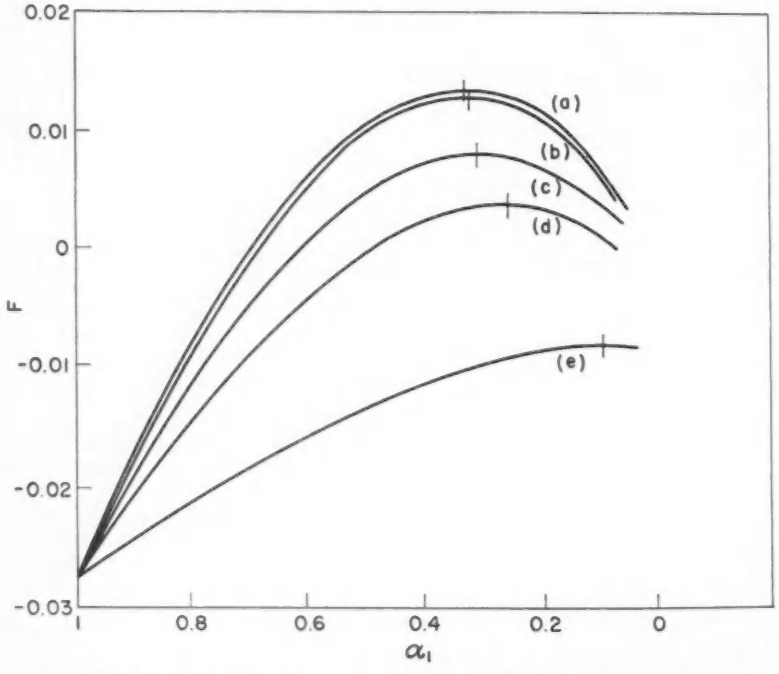
Proof:

Differentiate F_m with respect to A keeping Kt constant

$$\frac{\partial F_m}{\partial A} = \left[\frac{Kt}{3A^2} - \frac{K^2t^2}{27A^2} - \frac{2K^3t^3}{27A^3}\right]\left[Kt + \ln\left(1 - \frac{Kt(A+1)}{3A} + \frac{K^2t^2(A^2+A+1)}{27A^2}\right)\right]$$

On the right hand side of the equation both expressions enclosed in square brackets are positive in the interval $O < Kt < 1$. Therefore, F_m must increase continuously as A increases from 1.

This is illustrated by an example in Figure-Appendix 3 with Kt equal to 0.5, the maximum increases from a negative value when A is equal to 2 to a positive value of about 0.013 when A is infinitely large.



Figure—Appendix 3. Relation between F and A when two crystal sizes are present and α_1 is varied, with Kt equal to 0.5. The vertical lines show the greatest possible positive values of F as A is increased from 2 to infinity. (a) A = infinity; (b) A = 100; (c) A = 10; (d) A = 5; (e) A = 2.

Appendix 4

Statement:

F'_m in the following equation increases continuously as Kt increases in the interval $0 < Kt < 1$.

$$F'_m = \frac{Kt}{3} - \frac{K^2t^2}{27} + \left(1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right) \ln \left(1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right)$$

Proof:

Differentiate F'_m with respect to Kt

$$\frac{dF'_m}{dKt} = \left[-\frac{1}{3} + \frac{2Kt}{27}\right]\left[\ln \left(1 - \frac{Kt}{3} + \frac{K^2t^2}{27}\right)\right]$$

On the right hand side both expressions enclosed in square brackets are negative in the interval $0 < Kt < 1$. Therefore dF'_m/dKt is positive and F'_m increases continuously in this interval.

AN INVESTIGATION OF THE INTERCEPT METHOD FOR DETERMINING THE PROPORTION OF DOLOMITE AND CALCITE IN MIXTURES OF THE TWO

II. Experimental rates of solution of dolomite and calcite in samples consisting of a number of crystals[1]

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ABSTRACT

Experimental results are presented which support conclusions derived from a theoretical analysis of the log V vs. t plot, representing the rate of solution of dolomite consisting of a number of crystals. Experimentally determined rates of solution of dolomite and calcite are presented. The intercept method for determining the proportion of dolomite and calcite in mixtures of the two is evaluated on the basis of the theoretical and experimental results.

INTRODUCTION

In Part I(4) of this investigation, a theoretical analysis was made of the rate of solution of a sample of dolomite, consisting of a number of crystals, in relatively concentrated hydrochloric acid. This was done by considering the characteristics of the log V vs. t plot, where V is the volume of dolomite present at any time (t) during the progress of the reaction. It was shown that the plot, during the time required to dissolve about 50 per cent of the volume of the smallest crystal or crystals, could be concave either upwards or downwards, depending on the size distribution of the crystals present. Nevertheless, the deviations of the theoretical value of V from the straight line of best fit were always within limits, regardless of size distribution. This reasoning can be applied as well to the solution of calcite in hydrochloric acid. The only difference between the plots for the two carbonates should be in the slopes, caused by differences in the rate constants h(dolomite) and h(calcite) and by any difference that might exist in the shape of the crystals. The latter should be of minor importance because of the similarity in the crystal structure of the two carbonates.

The effect of the shape of the crystals on the slope of the log V vs. t plots was simplified in Part I by assuming that the dolomite crystals were cubes. In this way h always occurred multiplied by k in the equations where k is equal to the ratio of the surface area of a cube to its volume raised to the two thirds power. In real samples, k can be assumed to be some kind of average value for a sample so that k and h will always occur in the combination kh as before. A precise value for h separate from k cannot be obtained from experiments with samples consisting of a number of crystals without entailing a prohibitive amount of work, counting and measuring crystals under a microscope. Similarly, an exact knowledge of h, determined with single crystals, is of limited value in predicting rates of solution of a sample of small crystals, unless the dimensions of the individual crystals are known in detail. Estimates of kh(dolomite) and kh(calcite) reliable within limits are necessary, however, before an evaluation of the intercept method (3) can be made.

In this part of the investigation experiments were made with two objectives in mind, (a) to provide evidence in support of the theoretical

[1]Contribution No. 7, Soil Research Institute, Canada Department of Agriculture, Ottawa, Ont.

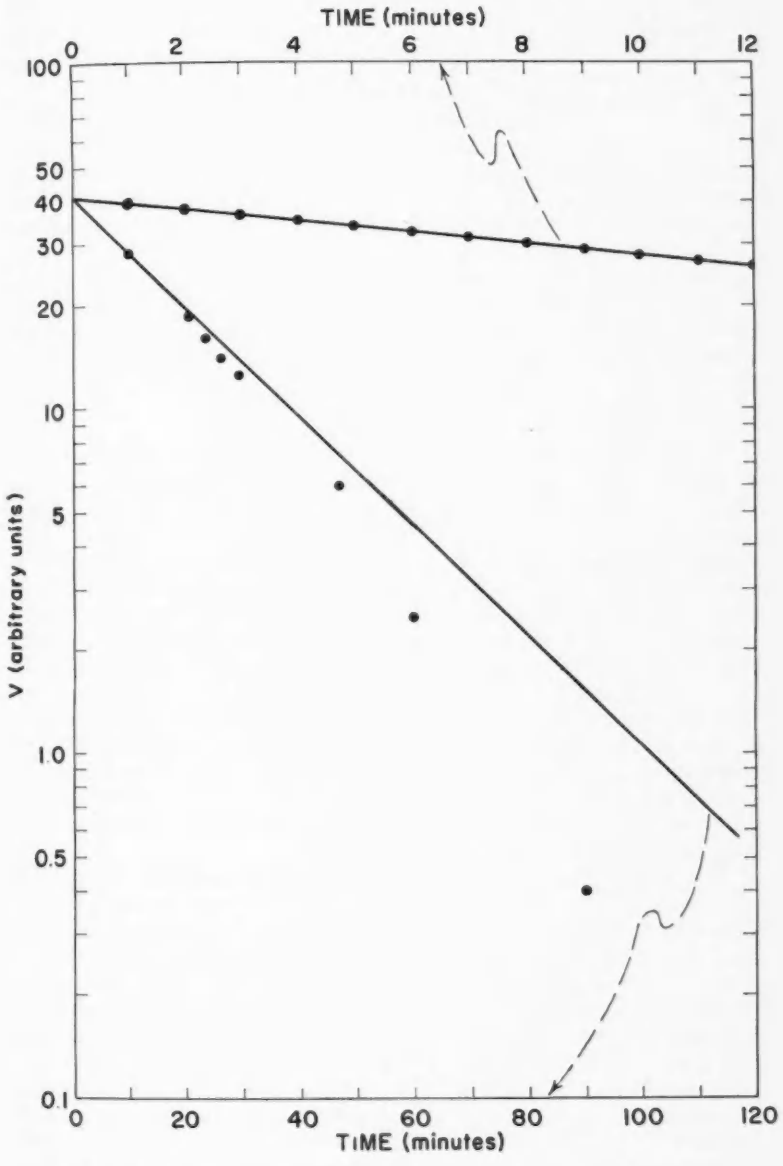

FIGURE 1. Log V vs. t plot for dolomite with all the crystals in the sample approximately equal in size.

analysis of Part I(4) and (b) to obtain reliable estimates of kh(calcite) and kh(dolomite). Finally the intercept method (3) is considered in the light of the results from the theoretical and experimental investigations.

EXPERIMENTAL

All experiments were made in a temperature controlled water bath at 25°C. unless otherwise stated. The dolomite and calcite used were naturally-occurring specimens and total analysis showed them to be relatively free from impurities. The samples were carefully ground to various sieve sizes. The ground samples were examined under a microscope and in some cases a rough estimate of the dimensions of the crystals present was made. In one experiment dolomite was ground to very small crystals and a size fraction was isolated by means of sedimentation (2). The rate of solution of the two carbonates was determined using the conditions and procedure described for the intercept method (3).

RESULTS AND DISCUSSION

Comparison of Experimental with Theoretical Results

The results in Figure 1 were obtained with a sample of dolomite which had passed a 100- but stayed on a 140-mesh sieve. Examination under a microscope showed that the crystals did not vary in size by more than a factor of two. The log V vs. t plots were, therefore, for a sample which approximated one in which the crystals were uniform in size. It was shown in Part I that the log V vs. t plot for the model approximated here should be concave downwards. It was shown further, however, that the plot should not deviate from the line of best fit by more than $\pm 0.018\ V_o$ until about 50 per cent of the sample is dissolved, i.e., until Kt is equal to about 0.6. With the arbitrary unit used in Figure 1, $0.018\ V_o$ corresponds to 0.7. It can be seen that the experimental log V vs. t plot is in agreement with the theoretical analysis. The plot did not deviate measurably from a straight line for the first 12 minutes (*upper curve*). After V had decreased to 50 per cent of its initial value, however, there was a measurable deviation in a downward direction from the straight line (*lower curve*) and the deviations increased in magnitude with time.

In another experiment the sample of dolomite consisted of large and small crystals, equal amounts of each of the two sizes by weight. The large crystals were those which passed a 100- but stayed on a 140-mesh sieve. The small crystals were isolated by means of sedimentation and they ranged in effective diameter from 5×10^{-4} to 20×10^{-4} cm. The average effective diameter of the small crystals was thus about 12.5×10^{-4} cm., while the large ones, according to the sieves used, were about 10 times larger. Equations (8) and (11) of Part I applied to the model approximated in this sample showed that the log V vs. t plot should be concave upwards while the small crystals are dissolving, but that during the time required to dissolve about 60 per cent of the sample represented by the small crystals the deviations from the line of best fit should not be greater than $\pm 0.025\ V_o$ (± 0.9 in Figure 2). The plot in Figure 2 was apparently linear for the first 2.5 minutes (*upper curve*) or until between 60 and 70 per cent of the volume represented by the small crystals was dissolved. It then deviated

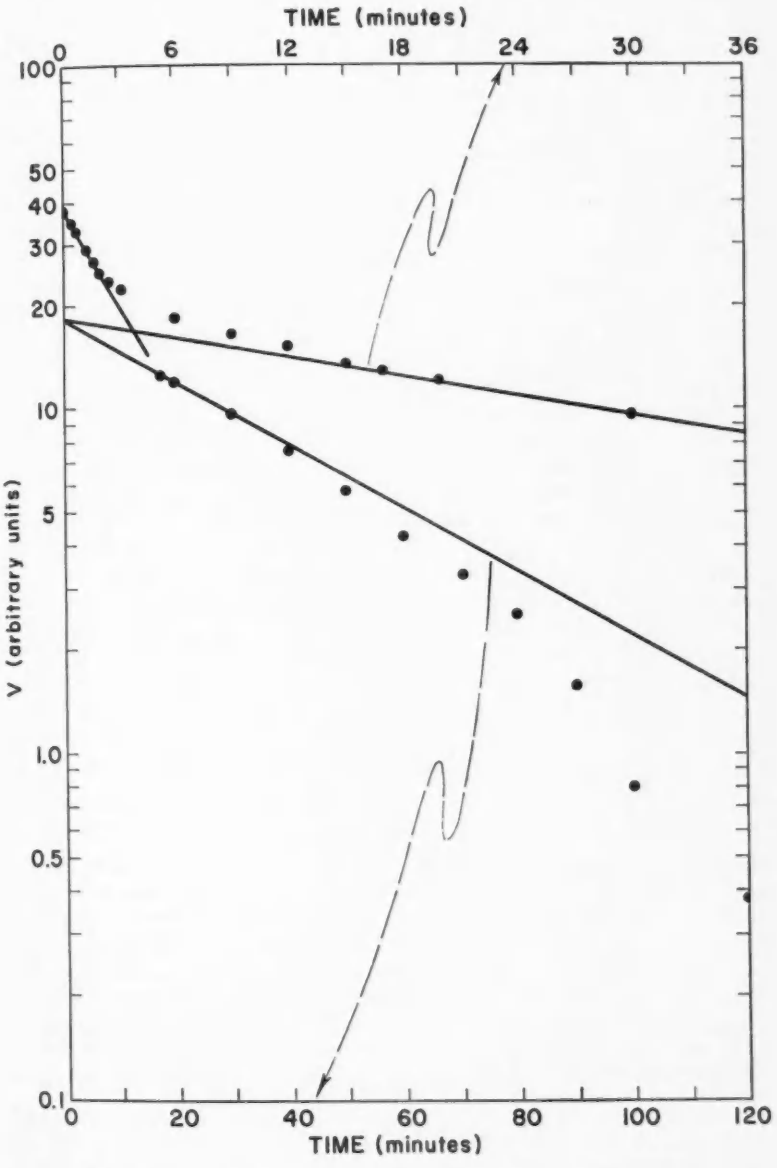

FIGURE 2. Log V vs. t plot for dolomite with two crystal sizes in the sample, 50 per cent of each by weight.

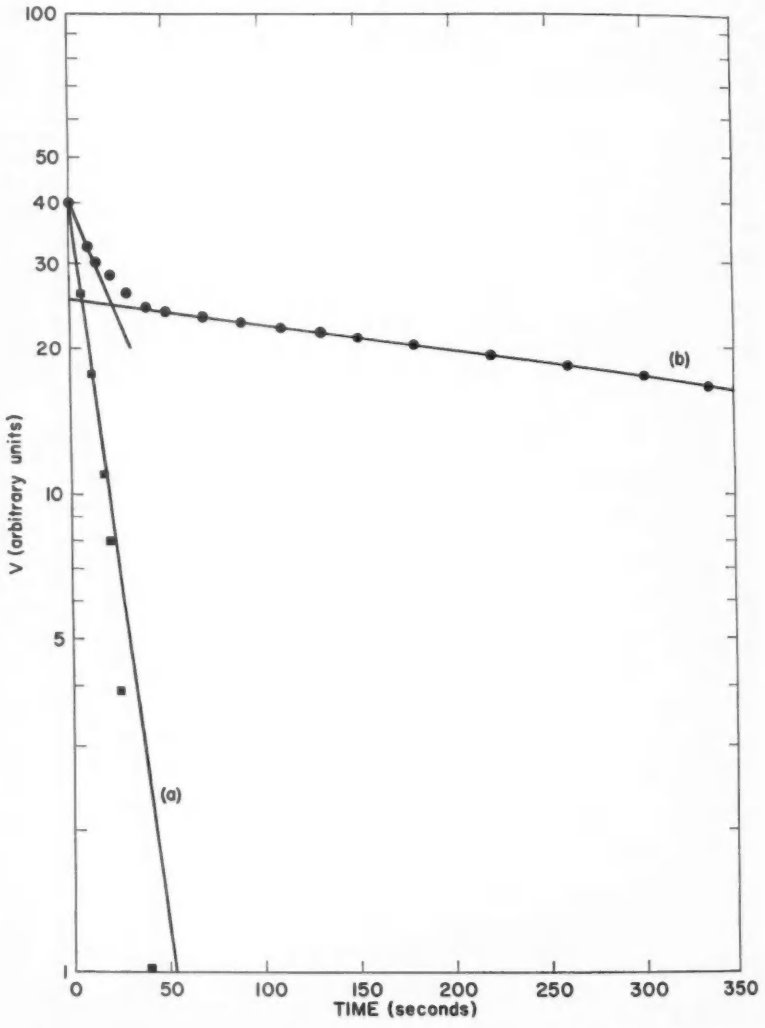

FIGURE 3. Log V vs. t plots for dolomite and calcite. (a) calcite with all crystals in the sample approximately equal in size. (b) mixture of calcite and dolomite, 38 per cent by weight calcite.

measurably from the straight line and was concave upwards for somewhat more than 12 minutes. After 12 minutes the plot followed a straight line until about 50 per cent of the volume of the large crystals was dissolved, after which it was concave downwards. Thus in all respects the plot representing the experimental results followed a path predicted by the theoretical analysis.

The experiment with a mixture of dolomite and calcite (Figure 3) was designed to approximate the model, discussed in Part I, which causes the maximum positive deviations from the line of best fit while the smallest crystals are dissolving. This model represented a sample in which there are two crystal sizes, the larger being extremely large compared with the smaller, and with about 38 per cent by weight of the sample represented by the small crystals. In the mixture used, calcite was substituted for the small dolomite crystals. The calcite crystals were completely dissolved in less than 60 seconds [curve (a) Figure 3] while the dolomite crystals required more than 100 minutes to dissolve completely (not shown in the Figure). The sample, as far as rate of solution was concerned, was thus equivalent to one containing two crystal sizes of dolomite, the large ones being more than 100 times larger than the small ones. Curve (a) shows that, with calcite alone, the plot was concave downwards but until more than 50 per cent of the sample was dissolved it could be represented by a straight line. With the mixture of calcite and dolomite [curve (b)], the plot was concave upwards during the time required to dissolve the calcite present (about 50 seconds). During the time required to dissolve roughly 50 per cent of the calcite, however, the plot could be represented reasonably well by a straight line. After 50 seconds the plot was linear for 350 seconds but, although it is not shown in the figure, it eventually deviated from the straight line and was concave downwards.

Thus, in all three experiments the agreement between experimental results and those predicted by the theoretical analysis was as good as could be expected, considering the difficulty of approximating exact models by real samples. In the light of this kind of agreement with experiments, there does not seem to be any reason to doubt the validity of the conclusions drawn from the theoretical analysis of the log V vs. t plot presented in Part I(4). Consequently, the intercept method (3) will be evaluated using the assumption that these conclusions are sound.

Experimental Rates of Solution of Dolomite and Calcite

Before discussing the intercept method, it was necessary to have reliable estimates of kh(calcite) and kh(dolomite) for conditions used in the method. Ferrari and Sessa (1) determined kh(calcite), in 2 N HCl using single crystals, at a number of temperatures and found a value of about 1.5×10^{-3} cm. per second at 25°C. They determined kh(dolomite) at 95°C. in 60 per cent perchloric acid plus HCl. They then assumed that the effect of temperature was the same for kh(calcite) and kh(dolomite) and, by a series of comparisons involving another metal carbonate, arrived at a value for kh(dolomite) of about 10×10^{-6} cm. per second at 25°C. Since the conditions used by Ferrari and Sessa were somewhat different from those used in the intercept method, experiments were made to estimate the value of kh for both dolomite and calcite at a number of temperatures.

The sample of dolomite used in these experiments was examined under a microscope. It was observed that the crystals were fairly uniform in shape; the longest side observed for the crystals was 0.1 mm. and the shortest was about 0.05 mm. The temperatures used were 12.5, 24 and

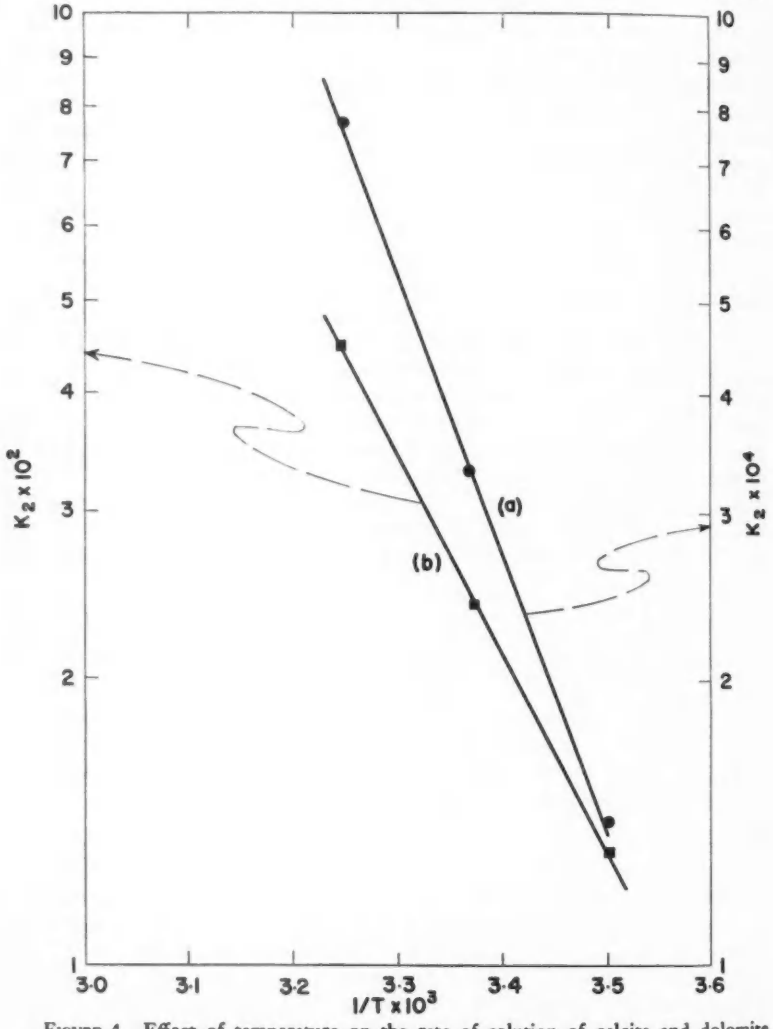

FIGURE 4. Effect of temperature on the rate of solution of calcite and dolomite. (a) dolomite. (b) calcite.

35°C. It was shown in Part I(4) that the negative of the slope of the log V vs. t plot, during the time required to dissolve roughly 50 per cent of the sample, is an estimate of K_2. This K_2 is equal to $(0.43\ kh/a)\Sigma\alpha_i/x_i$ and all the terms in this expression, except the rate constant h, are constant for a particular sample and independent of temperature. It follows, therefore, that the energy of activation for the solution of dolomite can be calculated from the slope of the log K_2 vs. 1/T plot, where T is the temperature on the absolute scale.

The slope of the log V vs. t plot was determined for the interval between zero time and the time required to dissolve 50 per cent of the sample at each of the three temperatures. Curve (a) in Figure 4 shows that the log K_2 vs. 1/T plot was linear. From the slope of this plot the energy of activation for the solution of dolomite was calculated to be 13,500 calories per mole.

The value of K_2 at 25°C. read from curve (a) in Figure 4 was 3.65×10^{-4} per second. If all the crystals in the sample were cubes with sides equal to 0.05 mm. (the smallest observed) the calculated kh would be 4.25×10^{-6} cm. per second while if they were cubes with the largest side observed, kh would be 8.50×10^{-6} cm. per second. It is safe to say, therefore, that kh(dolomite) for conditions used in the intercept method was $6.4 \pm 2.2 \times 10^{-6}$ cm. per second.

The sample of calcite used to estimate kh for calcite varied somewhat more in crystal size than did the dolomite sample. The longest side observed for a crystal was 1.2 mm. and the shortest was about 0.4 mm. The value of kh(calcite), estimated from experiments done at 25°C., was $5.5 \pm 2.7 \times 10^{-3}$ cm. per second.

The reaction was too rapid with calcite to establish the slope of the log V vs. t plot when the experiments were done at 35°C. The acid concentration was therefore reduced from 4 N to 2 N. This reduced the rate of the reaction by a factor of about 0.6. Even at this slower rate it was necessary to determine the values of K_2 from 50 to 75 per cent of complete solution rather than from zero to 50 per cent. The log of K_2 determined in this way was plotted against 1/T in Figure 4. Curve (b) shows that the three points fall on a straight line. The energy of activation for the solution of calcite calculated from the slope of this line was about 9,500 calories per mole.

The value of $6.4 \pm 2.2 \times 10^{-6}$ cm. per second for kh(dolomite) at 25°C. found in this investigation was somewhat smaller than 10×10^{-6} calculated from the experiments reported by Ferrari and Sessa (1). This difference is probably caused by two things. First, their solvent was 95 per cent perchloric acid plus some HCl whereas in this investigation the solvent was 4 N HCl. Second, they assumed that the effect of temperature was the same for kh(calcite) and kh(dolomite) whereas it was shown above that there is a real difference between the energies of activation for the solution processes of the two carbonates. The value for kh(calcite) of 1.5×10^{-3} at 25°C., found by Ferrari and Sessa, is lower than $5.5 \pm 2.7 \times 10^{-3}$ cm. per second estimated from the results of this investigation. This difference can be explained by the fact that they used 2 N HCl whereas 4 N HCl was used for the results reported above. It was found in this investigation that when 2 N HCl was used instead of 4 N HCl the rate of solution of calcite was reduced by a factor of about 0.6. Considering the differences in the conditions used, the values for both kh(calcite) and kh(dolomite) found in the two investigations agree reasonably well. It can be concluded, therefore, that with the conditions used in the intercept method (3), kh(calcite) is not less than 2.8×10^{-3} and kh(dolomite) is not greater than 8.6×10^{-6} cm. per second.

EVALUATION OF THE INTERCEPT METHOD (3)

The intercept method requires the calcite in the sample to be completely dissolved in 60 seconds. Any calcite crystal will be completely dissolved when Kt for it is equal to 3 (see equation 12, Part I). It can be calculated, therefore, since kh(calcite) is not less than 2.8×10^{-3} cm. per second, that, if the effective diameter of the crystal is not greater than 5.6×10^{-2} cm., the crystal will be completely dissolved in 60 seconds. Consequently, if the sample has passed a 0.5-mm. sieve it meets this requirement of the method.

It was shown, by the analysis in Part I, that during the time required to dissolve about 50 per cent of the smallest dolomite crystal present (kht/a equal to 0.6) the log V vs. t for all the dolomite in the sample will not deviate from the line of best fit by more than $\pm 0.018V_o$ or 1.8 per cent of V_o. For the intercept method, the authors(3) report a standard deviation for duplicate determinations of $\pm$ 1.2 per cent of the dolomite present; this is equivalent to $\pm$ 2.4 per cent at the P.05 level. It appears, therefore, that within the experimental error of the method the log V vs. t plot should be linear until about 50 per cent of the smallest crystal of dolomite is dissolved. Since 60 seconds must be allowed for complete solution of the calcite present, a total of at least 120 seconds should be allowed for solution of 50 per cent of the smallest dolomite crystal. Otherwise, it may not be possible to establish the experimentally linear part of the log V vs. t plot to extrapolate to zero time. Because kh(dolomite) is not greater than 8.6×10^{-6} cm. per second, it can be calculated that the smallest dolomite crystal in the sample must have an effective diameter of at least 1.7×10^{-3} cm.

Nothing has been said, as yet, concerning the possibility that crystal size distributions might exist which would cause the log V vs. t plot to be experimentally linear for an interval of time much beyond that required to dissolve 50 per cent of the smallest crystal present. It can be shown, in fact, that a great number of such size distributions do exist. For example, if there is a certain regular distribution of sizes from the smallest to the largest, the plot will be linear within the error of the method until about 50 per cent of the dolomite in the sample is dissolved. This regular distribution is the one in which the smallest crystal has an effective diameter of a, the next smallest $2a$, the next $3a$ and so on to the largest, with a sufficiently small. Furthermore, it can be shown that if all the crystals below a certain size are missing from this model, the plot may still be linear within the usual error until 50 per cent of the sample is dissolved. With this in mind, the reliability of the intercept method can be considered for samples in which there are crystals of dolomite with effective diameters less than 1.7×10^{-3} cm.

If the smallest crystal of dolomite in the sample requires more than 60 seconds to dissolve completely, it will have an effect on the purely dolomite part of the log V vs. t plot in the presence of calcite. Any dolomite crystal with an effective diameter greater than 1.7×10^{-4} cm. will require more than 60 seconds to dissolve. Consequently, if the smallest dolomite crystal has an effective diameter greater than 1.7×10^{-4} but less than 1.7×10^{-3} cm., the plot will be linear for some time directly after

60 seconds with some size distributions and will be non-linear with other distributions. If there is a linear part of the plot of sufficient magnitude to establish its slope, the results from the intercept method will be valid. If, on the other hand, there is not a linear part to the plot directly after 60 seconds, it will be obvious that the intercept method cannot be used.

With samples which contain some dolomite crystals which have effective diameters less than 1.7×10^{-4} cm. it is possible to have size distributions such that the log V vs. t plot directly after 60 seconds is linear and for which the results by the intercept method are valid. There is no way of knowing, however, whether the results are valid or not. It would be possible, for instance, to have some fraction of the dolomite represented by crystals so small that they would dissolve at the same rate as the largest calcite crystals, while the size distribution of the remainder of the dolomite is such that there is a linear part to the log V vs. t plot for them, which could be extrapolated to zero time.

This discussion of the intercept method can be summed up as follows. The sample must pass a 0.5-mm. sieve. If the smallest dolomite crystal has an effective diameter greater than 1.7×10^{-3} cm., the method is in every case fundamentally sound within the error claimed for it. If the effective diameter of the smallest crystal is greater than 1.7×10^{-4} cm. the method will give a valid estimate of the dolomite present or it will be obvious from the shape of the log V vs. t plot that the method cannot be used. If there are dolomite crystals present whose effective diameters are less than 1.7×10^{-4} cm. the method may or may not give a valid estimate of the proportion of dolomite in the sample.

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THE EFFECT OF RAINDROP SIZE AND IMPACT VELOCITY ON SAND-SPLASH

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ABSTRACT

A mathematical relationship was developed which gives the amount of sand splashed from a splash cup when raindrop size and impact velocity are known. The amount of sand splashed was used as an index of the effective energy of the raindrops.

This relationship is expressed as: $G = KDV^{1.4}$ where G is the amount of sand splashed (gm.), K is a constant for the sand, D is the diameter of the drops (mm.), and V is the impact velocity of the drops (m./sec.).

INTRODUCTION

The importance of raindrop energy as an influence in erosion of soil has been widely recognized. Raindrops may be of different sizes and each storm may contain drops in a particular size range (6). When a raindrop falls to a soil surface, it dissipates its energy on that surface. This may cause movement and/or breakdown of soil particles. The splashed soil is available for transport if surface run-off occurs. On sloping land more soil splashes in the downhill than in the uphill direction. This is an important factor in sheet erosion. Continual splashing causes separation and orientation of particles which may contribute to the sealing of the soil surface.

The effective energy in a rainfall can be determined by measuring the amount of standard sand which is splashed from a unit area (2, 3). Ellison (2) used standard splash cups but it was found necessary to make a correction for the amount of sand splashed from these to allow for the lowering of the sand surface relative to the rim of the cup as sand was splashed out. This correction formula given by Bisal (1) can be written as $G = \left\{ 0.772 + 2.057 \left(\frac{g}{24.71} \right)^{1.481} \right\} 9.45$, where G is the amount of sand (grams) splashed from a level surface and g is the amount of sand (grams) splashed from a standard splash cup.

The purpose of the work reported here was to evaluate the effective energy in raindrops of a given size striking a surface at a particular velocity. The quantities of sand splashed from containers was used as an index of the effective raindrop energy.

MATERIALS AND METHOD

A rainfall simulator was used in this study. It consisted of a muslin cloth placed over a chicken wire screen with a 1-inch mesh*. Depressions were made in the cloth corresponding to the inch-square openings in the screen. A wool string about 2 inches long was threaded through the cloth in each depression. The drops fell from these strings when water was sprayed on to this simulator screen from a nozzle mounted above.

The range of drop size used was limited due to the interacting effect of string diameter and surface tension, but it was possible to obtain drops of three sizes, viz., 4.88, 4.52, and 4.13 millimetres (4) by the use of wool string.

Cotton string was tested in an attempt to reduce the size of the drops but it proved unsatisfactory because of variability in wetting. Nylon string

*Blueprints available for a copper type permanent screen.

was tried but it also was unsatisfactory due to the resistance of nylon to wetting.

Conventional and constant levelling cups* (1) were used to determine the amount of sand splashed. The latter had a manually operated device for keeping the sand surface level with the rim of the cup. Two of each type of cup were placed on a table which was rotated under the raindrop simulator at a constant speed.

The height of fall of the raindrops was varied from 2.44 to 7.01 metres to give the range of impact velocities (5) desired. A minimum fall of 2.44 metres was used since below this height the impact velocity of the drops was too low to establish the relationships under study.

A cloth soaked in a wetting agent was placed over the drainage holes in the bottom of each cup to allow for the disposal of the water at a rate equal to the percolation rate through the sand. The collecting jar was also vented so that there would be no build-up of inside pressure as the jar filled.

Rainfall intensity was varied from 3 to 6 inches per hour and the amount of sand splashed in relation to a particular intensity was evaluated. No significant relationship was found between intensity and amount of sand splashed ($r = 0.306$) as long as no free water built up on the surface of the sand.

The amount of rainfall used to evaluate splash vs. raindrop size and velocity was arbitrarily set at 4 inches and the amount actually obtained was 3.97 inches. This was applied at a rate approximating 4 inches per hour.

RESULTS AND DISCUSSION

Sand Splash and Drop Size

Data showing the amount of sand splashed in relation to the size and impact velocity of raindrops are given in Table 1. The values for each drop size were put in graph form (not shown). An arbitrary impact velocity of 7.4 m./sec. was then selected and the corresponding amounts of sand splash for drops of each size were taken from the graphs. This information is presented in Figure 1.

*Blueprints available for constant levelling cups.

TABLE 1. — THE EFFECT OF RAINDROP SIZE AND VELOCITY ON AMOUNT OF SAND SPLASHED
3.97 inch simulated rain — average four replicates

4.13 mm.			4.52 mm.			4.88 mm.		
Height	Velocity	Sand splashed	Height	Velocity	Sand splashed	Height	Velocity	Sand splashed
m.	m./sec.	gm.	m.	m./sec.	gm.	m.	m./sec.	gm.
						2.44	6.25	136
						3.05	6.80	154
3.90	7.12	140	3.66	7.20	154	3.66	7.25	170
4.57	7.48	148	4.57	7.70	169	4.57	7.75	185
						5.49	8.15	197
			6.10	8.26	188	6.10	8.35	203
						7.01	8.62	214

Note: C.V. for any of the data in Table 1 did not exceed 0.03.

FIG. 1

SPLASH IN RELATION TO DROP SIZE
3.97 INCH OF SIMULATED RAINFALL
VELOCITY OF FALL = 7.4 METERS PER SEC.

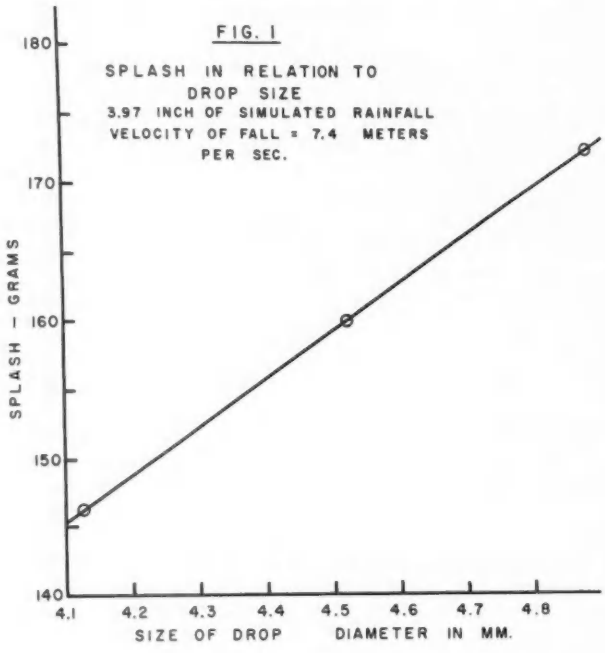
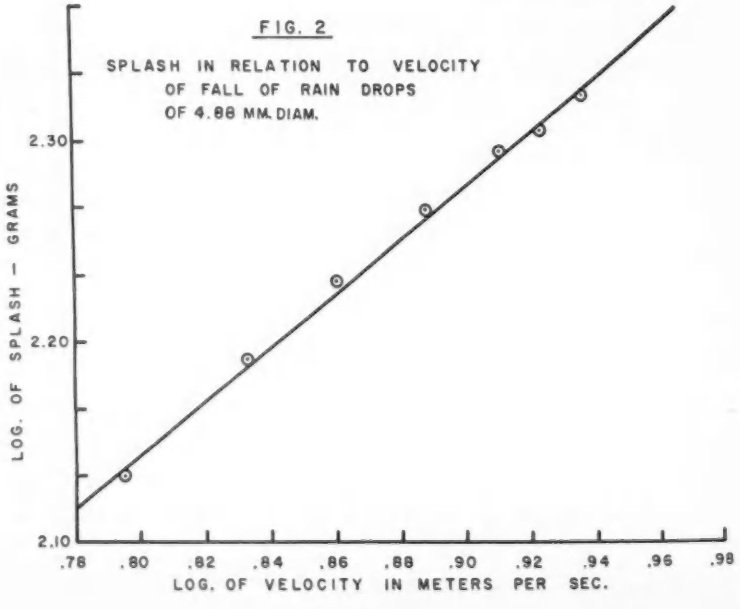


FIG. 2

SPLASH IN RELATION TO VELOCITY OF FALL OF RAIN DROPS OF 4.88 MM. DIAM.



It is seen from this figure that there was a linear relationship between sand splashed and drop size. This relationship is expressed as

$$G = K_1 D \quad (1)$$

where G is the amount in grams of sand splashed, K_1 is a constant and D is the diameter of the raindrops.

Sand Splash and Impact Velocity

The data for the 4.88-mm. drops were taken from Table 1 and presented in Figure 2 in log form. The log relationship between the amount of sand splashed and impact velocity is linear. The gradient is 1.4. This relationship is written as:

$$G = K_2 V^{1.4} \quad (2)$$

where G is the amount (in grams) of sand splashed, K_2 a constant and V is the impact velocity (in m./sec.) of the raindrops. Combining equations (1) and (2) the relationship between amount of sand splashed and size and velocity of raindrops becomes

$$G = KDV^{1.4}$$

where K is a constant for the standard sand.

A value of $V^{4.33}$ was suggested in other work (2) but this figure included detachment and transportation of the sand instead of just detachment.

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A COMPARATIVE STUDY OF A SULPHUR RESPONSIVE AND A NON-RESPONSIVE GREY WOODED SOIL[1]

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ABSTRACT

A chemical and biological comparison was made of the profiles of a sulphur-responsive (Loon River loam) and a non-responsive (Garrick loam) Grey Wooded soil. Both soils were found to contain relatively large quantities of barium, but the Loon River soil had larger quantities of readily soluble barium than the Garrick soil. Although both soils were found to be capable of precipitating sulphate in an acid medium, the Loon River precipitated more sulphate than the Garrick. This precipitation was found to occur both within the soil and in an acid extract of the soil. Barite was found in the 6- to 8-inch and 22- to 26-inch horizons of the Loon River soil, but not in any horizon of the Garrick soil. It was found that with either incubation or seedling extraction the Loon River soil did not release nearly as great a quantity of soluble sulphate as the Garrick soil, while on incubation it did release a quantity of nitrate equivalent to that released by the Garrick soil. The Loon River soil was found to contain markedly lower quantities of both total and acid soluble sulphate in the C horizon. It also contained a lower quantity of organic matter and exchangeable bases in the surface soil.

INTRODUCTION

The so-called Grey Wooded soils were first studied and described in Western Canada, where they occupy more than one hundred million acres of the forest region. Experimental work by the University of Alberta and the Canada Department of Agriculture on some of the Grey Wooded soils showed that small applications of sulphur (20 pounds per acre), gypsum, or any soluble sulphate salt resulted in increased crop yields (17).

Lawton (8), in summarizing the sulphur aspects of the chemical composition of soils, stated that: "Sulphur is present in soils in both the inorganic and organic forms. In the humid regions, where the organic matter of the mineral soils does not exceed 5 per cent, the bulk of the sulphur is present in such minerals as pyrite or marcasite (FeS_2), minor amounts of sphalerite (ZnS.), chalcopyrite ($CuFeS_2$), cobaltite (CoAsS), and varying quantities of gypsum ($CaSO_4.2H_2O$) and epsomite ($MgSO_4.7H_2O$). Generally field soils of the humid temperate regions have 50 to 500 p.p.m. of sulphate soluble in water or weak acids. The total sulphur content of the soils of these regions is about 0.05 per cent within a range of 0.01 to 0.15 per cent." Conrad (4), reporting on work done in California, stated that soil organisms may compete with higher plants for the small amounts of sulphate available in deficient soils.

Bentley *et al.* (1) have shown that crops can recover a considerable quantity of sulphate-sulphur placed at a 22-inch depth. However, these same workers reported that the total sulphur content of soils is very variable and "does not appear to be a suitable means of determining responsiveness to sulphur fertilization."

Recent work on the Loon River and Garrick Grey Wooded soils in Saskatchewan has revealed that the Loon River soil gives a marked response to sulphur, while the Garrick soil does not (2). These are typical upland Grey Wooded soils and have been described as such by Moss and St.

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Arnaud (10). There has been little detailed study of these soils. No accepted diagnostic technique other than field experimentation has been developed for sulphur requirements. The present study was designed to measure various soil factors that might be related to sulphur supply in an effort to find a reason for deficiency and a method of predicting crop response.

MATERIALS AND METHODS

Areas were selected to represent the sulphur-responsive Loon River loam and the non-responsive Garrick loam. Soil sampling was done according to a pre-determined plan. An area of approximately 1 acre on one farm (S.W. 32-58-21-W3) was selected to represent the cultivated Loon River series and another farm (S.W. 26-52-19W2) to represent the cultivated Garrick series. Each area was divided into two, and profile samples were procured from two sites in each subdivision. The horizons present in each soil differ somewhat as to their depths. The A_2 horizon is represented by samples taken at the 0-6 inch depth in each soil, and the A-B horizon by samples taken at a 6-10 inch depth in the Garrick soil; the B_1 horizon by samples taken at a 6-8 inch depth in the Loon River soil and at a 10-15 inch depth in the Garrick soil; the B_3 horizon by samples taken at the 22-26 inch depth in the Loon River soil; and the C_1 horizon by samples taken at a 34-38 inch depth in the Loon River soil and a 28-34 inch depth in the Garrick soil. These samples were composited for each horizon and studied for total sulphur, sulphate-sulphur, barium and barite presence and distribution, and for ability to release sulphate-sulphur to seedlings. They were also studied for their ability to precipitate sulphate-sulphur in an acid medium.

In addition to the profile samples, eight composite samples of surface soil (0-6 inch depth) were procured from each subdivision, which had been further subdivided for this purpose. These individual soil samples were studied for pH and sulphate-sulphur content. The surface soil samples from each subdivision were composited into samples 1 and 2 for each soil for general chemical characterization. They were further composited for incubation and other studies.

All samples were collected in the spring, just before the commencement of active growth. They were air-dried and ground to pass a 2-mm. sieve.

Soil pH was determined with a Beckman model H-2 pH meter, using a 1:1 soil-water ratio. Total soil sulphur was determined by the methods outlined in A.O.A.C. (11) and in "Chemistry of the Soil" (13). Soluble soil sulphates were determined by the method outlined by Chesnin and Yien (3) after extraction with 0.1N HCl, 1.0N NH_4OAc (ammonium acetate) or water using a 1:2 soil-extractant ratio. Soluble barium was extracted with 0.1N HCl and qualitatively identified by spectrogramming the precipitate caused by the addition of $(NH_4)_2SO_4$ and quantitatively by the method outlined in the A.O.A.C. (11). Analysis for nitrogen, organic matter, acid soluble and adsorbed phosphorus, exchange capacity and exchangeable bases were conducted according to standard recognized procedures (12). Carbon used in soil extractions was freed of sulphates by boiling and leaching with hydrochloric acid, ammonium acetate and water.

A petrographic study was conducted on the sands of the profile samples of each soil. Composite surface samples of the two soils were subjected to semi-quantitative spectrographic analysis. To determine if barium was on the exchange complex, the two soils were extracted for 30 minutes and 12 hours each with a 1:2 soil-extractant ratio using solutions of 1.0N KCl and 0.1N HCl. Approximately 0.5 grams of dry $(NH_4)_2SO_4$ was added to each extract and the turbidity was read in a Klett colorimeter using a blue filter. The effect of hydrogen ion concentration on the precipitation of sulphate was studied by using HCl at various normalities containing 20 p.p.m. of sulphur added as K_2SO_4 as the extractant, and determining the per cent sulphur recovered after a 20-minute extraction. The pH of the extract was also determined.

The biological release of sulphate-sulphur and nitrate-nitrogen was studied in general accord with the method for nitrates outlined by Fitts *et al.* (7). Fifteen-gram samples of the surface layer of each soil were incubated for a period of 2 weeks and then leached with water. The effect of added plant material and elemental sulphur on nitrate and sulphate release during incubation was also studied. To certain 15-gram samples of each soil was added 0.5 grams of ground alfalfa, which was free of

TABLE 1.—QUANTITY OF VARIOUS SOIL CONSTITUENTS IN SURFACE SOIL SAMPLES OF EACH SOIL

Constituent	Unit of measure	Loon River loam sample		Garrick loam sample	
		1	2	1	2
Nitrogen	per cent	0.16	0.15	0.31	0.27
Organic matter	per cent	3.73	3.79	7.68	6.87
Exchangeable potassium	me./100 gm.	0.19	0.22	0.50	0.57
Exchangeable calcium	me./100 gm.	8.18	8.89	16.14	17.58
Exchangeable magnesium	me./100 gm.	1.08	1.20	5.89	3.50
Base exchange capacity	me./100 gm.	9.57	9.85	23.02	20.74
Bray acid soluble and adsorbed phosphorus	p.p.m.	19.9	25.9	31.0	72.3
Bray adsorbed phosphorus	p.p.m.	14.0	17.5	16.6	35.9

TABLE 2.—THE DISTRIBUTION OF TOTAL SULPHUR AND OF SULPHATE-SULPHUR EXTRACTABLE WITH 0.1N HCl AND NH_4OAc (pH 6.7)

Loon River loam				Garrick loam			
Depth	Total sulphur	Extractant		Depth	Total sulphur	Extractant	
		HCl	NH_4OAc			HCl	NH_4OAc
	%	Sulphur p.p.m.	Sulphur p.p.m.		%	Sulphur p.p.m.	Sulphur p.p.m.
0-6″	0.015	1	1	0-6″	0.018	2	4
6-8″	0.006	5	1	6-10″	0.018	0	2
22-26″	0.013	3	2	10-15″	0.025	3	6
34-38″	0.014	14	16	28-34″	0.049	22	8

water soluble SO_4, and to others 0.0015 grams of elemental sulphur. The quantity of nitrate-nitrogen and sulphate-sulphur in the extract was determined for each.

The seedling extraction test was according to the Neubauer method as outlined by Stewart (15) except that spring barley was used in place of rye. One hundred-gram samples of surface soil and fifty-gram samples of C horizon were extracted. The roots and tops were harvested 11 days after seeding and analysed for total sulphur.

EXPERIMENTAL RESULTS

General Soil Analysis

The average pH of sixteen samples of surface soil, sampled over a one-acre area, in the Loon River soil was 6.7 with a range from 6.5 to 7.0 and, in the Garrick soil, was 6.8 with a range from 6.7 to 7.0. The average sulphate-sulphur content of the Loon River soil was 1.5 p.p.m. with a range from 0 to 3.0 p.p.m., while that of the Garrick soil was 3.4 p.p.m. with a range from 0 to 11.0 p.p.m. None of these results showed a consistent field pattern. The quantity of various soil constituents found in each soil are presented in Table 1.

The base exchange capacity, per cent nitrogen, per cent organic matter and exchangeable calcium values for the Loon River soil were quantitatively about half the values for the Garrick soil. The values of exchangeable potassium and magnesium for the Loon River soil were less than half of those for the Garrick soil. The phosphorus quantities were more variable between samples and the difference between the two soils was not so pronounced as in the case of the other constituents.

Distribution of Sulphur in the Soil

The distribution of total sulphur and of sulphate-sulphur extracted with 0.1N HCl and NH_4 OAc (pH 6.7) is set forth in Table 2.

The Garrick soil was found to be more adequately supplied with sulphur than the Loon River soil when the entire profile was considered. However, in the surface 6 inches of soil the difference between them was not pronounced; the Loon River soil contained about 300 pounds of sulphur per acre and the Garrick soil contained about 360 pounds of sulphur per acre.

The acid soluble fraction was not great in either soil. However, the data indicate a general increase with depth.

The quantity of NH_4OAc extracted sulphur increased generally with depth in both soils. The Loon River surface soil yielded negligible quantities, while the Garrick surface soil yielded small, but measurable quantities. The Loon River soil gave up approximately the same quantity to NH_4OAc from the C horizon as it did to the HCl extractant; however the Garrick C horizon yielded less to this extractant than to HCl.

Sulphate Precipitation by the Soil

On spectral analysis, barium was readily detected in all horizons of the Loon River soil. It was detected with difficulty in the two upper horizons of the Garrick soil, and not detected in the two lower horizons. Semi-quantitative spectrographic analysis for barium content showed the Garrick soil to contain 0.09 per cent barium and the Loon River soil 0.07

per cent. The Loon River soil determination was considered satisfactory, but, because of the presence of impurities, it was deemed necessary to conduct wet chemical analysis of the Garrick soil. The content by this method was found to be 0.07 per cent.

Petrographic study of the sands of the horizon samples of each soil revealed the presence of barite in only the 6- to 8-inch and 22- to 26-inch horizons of the Loon River soil.

The results of spectrogramming the precipitate caused by the addition of $(NH_4)_2SO_4$ to the acid extracts, were as follows:

(a) *Loon River* – Barium chiefly, with only traces of impurities

(b) *Garrick* – Calcium, magnesium, less barium, trace strontium, aluminum.

Difficulty was encountered in determining the quantity of barium in the acid extracts, but the quantities recorded were 15 p.p.m. in the Loon River extract and 11 p.p.m. in the Garrick extract. This difference in the quantity of barium extracted from the two soils is sufficient for the precipitation of 1.9 p.p.m. of sulphur.

An estimation of the quantity of barium extracted with HCl and KCl solutions is given in Table 3.

TABLE 3.—AN ESTIMATION OF THE QUANTITY OF BARIUM EXTRACTED FROM SURFACE SAMPLES WITH KCl AND HCl SOLUTIONS

Time	Extractant	Turbidity	
		Loon River loam	Garrick loam
30 minutes	0.1N HCl	17	9
	1.0N KCl	1	1
12 hours	0.1N HCl	25	12
	1.0N KCl	0	3

TABLE 4.—THE PRECIPITATION OF SULPHUR BY A HORIZON SAMPLES OF THE TWO SOILS FROM HCl EXTRACTANTS TO WHICH 20 P.P.M. S HAD BEEN ADDED AS K_2SO_4, AND THE pH OF THE EXTRACTS

Soil	Normality of extractant	pH of extract	Per cent recovery	Micrograms of sulphur precipitated per gram of soil
Loon River loam	Water	5.6	100	0.0
	.025	3.9	94	3.0
	.125	1.5	50	25.0
	.25	0.9	40	30.0
Garrick loam	Water	5.9	100	0.0
	.025	4.6	100	0.0
	.125	2.2	76	12.0
	.25	1.2	56	22.0

TABLE 5.—THE PRECIPITATION OF SULPHUR BY SURFACE SOIL AND C HORIZON SAMPLES FROM HCl AND NH_4OAc EXTRACTANTS TO WHICH 20 P.P.M. S HAD BEEN ADDED AS K_2SO_4

Soil and depth	0.1 N HCl+20 p.p.m. S		1.0N NH_4OAc(pH6.7)+20 p.p.m.S	
	Per cent recovery	Gain or loss of S from extractant p.p.m. of soil	Per cent recovery	Gain or loss of S from extractant p.p.m. of soil
Loon River loam 0-6″	64	−15.0	110	+ 4.0
Loon River loam 34″-38″	90	− 4.0	140	+16.0
Garrick loam 0-6″	98	− 1.0	115	+ 6.0
Garrick loam 28″-34″	228	+54.0	125	+10.0

TABLE 6.—THE RELEASE OF NITRATE-NITROGEN AND SULPHATE-SULPHUR BY INCUBATION OF SAMPLES OF THE A HORIZON OF EACH SOIL

Soil and treatment	Gain during 2-week period	
	Sulphate-sulphur p.p.m.	Nitrate-nitrogen p.p.m.
Loon River loam	2.5	35
Loon River loam plus plant material	0.0	22
Loon River loam plus elemental sulphur	15.5	35
Garrick loam	10.2	39
Garrick loam plus plant material	1.0	26
Garrick loam plus elemental sulphur	20.5	40

The barium was present in the soil in a form that was extracted with 0.1N HCl, but not with 1.0N KCl. This would indicate that it was in an acid soluble rather than an exchangeable form.

The effect of hydrogen ion concentration on the precipitation of sulphur by A horizon samples of the two soils is shown in Table 4.

In both soils the loss of sulphur from the extractant varied inversely with the pH of the extract and for approximately equivalent pH values the loss of sulphur was approximately equivalent. A greater amount of acidity was required in the extractant to alter the pH of the extract from the Garrick soil than from the Loon River soil.

The per cent recovery from surface and C horizon samples from each location, when extracted for 20 minutes with 0.1N HCl and 1.0N NH_4OAc (pH6.7) to both of which had been added 20 p.p.m. sulphur as K_2SO_4 (1:2 soil-extractant ratio), is shown in Table 5.

The surface soil results indicated in Table 5 reflect the findings in all of the recovery studies conducted, namely that there was considerable loss of sulphur from the acid extractant to the Loon River soil, while there was no appreciable loss or gain with the Garrick soil. In the Loon River subsoil it was found that, when sulphur was added in the acid extractant,

TABLE 7.—A MODIFIED NEUBAUER EXTRACTION OF SULPHUR BY BARLEY SEEDLINGS

Soil	Total micrograms of sulphur extracted	Micrograms of sulphur extracted per gram of soil	Yield of plants in grams of D. M.
Loon River loam surface 100 grams	600	6	2.60
Loon River loam C horizon 50 grams	300	6	3.34
Garrick loam surface 100 grams	1300	13	3.40
Garrick loam C horizon 50 grams	1000	20	3.27

there was a net loss to the soil in spite of the fact that an extraction with 0.1N HCl brought sulphur out of the soil. The NH_4OAc extraction however, resulted in a 16 p.p.m. gain from the C horizon of the Loon River soil. In the case of the Garrick C horizon there was a much smaller gain with NH_4OAc than with HCl.

Biological Oxidation of Soil Sulphur

The biological release of nitrate-nitrogen and sulphate-sulphur from samples of the surface soil of each location and the effect of added sulphur and plant material on the release is shown in Table 6.

The small trace of sulphur recorded for Loon River loam is within the realm of error because of difficulty encountered in procuring a non-turbid water extract of this soil, and because it represents a reading of about only one part per million in the extract. That the Loon River soil is capable of sulphur oxidation is indicated by the recovery of 15 of the 100 micrograms of sulphur added per gram of soil. The added plant material had the customary short-term effect of reducing nitrate release and this effect was even more pronounced with sulphate.

Seedling Extraction of Soil Sulphur

The quantity of sulphur extracted by barley seedlings from surface and C horizon soil samples is shown in Table 7.

Considerably more sulphur was extracted from the Garrick soil than from the Loon River and the quantity increased with depth in the Garrick, but not in the Loon River. The plants on the Loon River soil showed considerable evidence of yellowing and were quite spindly compared with those on the Garrick. Harvest 11 days after seeding was necessary because of the poor condition of the Loon River plants. The increased plant weight on the Loon River C horizon soil was largely due to root development.

Under almost ideal conditions barley seedlings extracted surprisingly large quantities of sulphur from both soils, but the study clearly showed the Loon River soil to be lacking available sulphur when compared with Garrick. The results obtained would substantiate that there is a difference in the ability of the two soils to supply sulphur for plant growth.

DISCUSSION

The Loon River soil showed a lower average content of soluble sulphate than the Garrick. However, the quantity was very low in both soils. The

wide variability found within each soil would practically rule out this determination so far as diagnosis is concerned.

The Loon River soil failed to release sulphur in a soluble sulphate form, either on incubation (Table 6) or to barley seedlings (Table 7), in a quantity comparable with that released from the Garrick. The Loon River soil is not capable of satisfactorily releasing the sulphur it was found to contain.

Based on sulphur to nitrogen and organic matter ratios given by Russell (14) and Evans and Rost (5) and the nitrogen and organic matter contents determined for the soils under study, the Loon River loam could have between 80 and 150 pounds of sulphur per acre in the organic fraction, and the Garrick loam between 140 and 290 pounds per acre in the same fraction. The remaining 150 to 220 pounds per acre in the Loon River loam and 70 to 220 pounds in the Garrick loam would thus be in mineral form. These mineral forms are not sulphates readily soluble in dilute acid or water. The ratio of soluble sulphate to nitrate released by incubation (Table 6) of the Garrick soil indicates that a large portion of the sulphur released came from the mineral fraction. The Loon River soil released approximately as much nitrate nitrogen as the Garrick on incubation, but failed to release any appreciable quantity of soluble sulphate. That the Loon River soil is capable of oxidizing elemental sulphur, when applied in liberal quantity, indicates that it is biologically capable of the oxidation of reduced forms of sulphur. Yet, the comparatively large portion of sulphur that it contains in the mineral form failed to be released on incubation.

Both soils contain relatively large quantities of barium in the surface layer, approaching the maximum content, 0.10 per cent, reported by Failyer (6) in his study of the inorganic composition of numerous American soils. The approximately 1,400 and 1,600 pounds of barium per acre, present in the Loon River and Garrick soils respectively, is sufficient to precipitate as $BaSO_4$ approximately 327 to 373 pounds of sulphur per acre, or 27 and 13 pounds more sulphur than the soils contain.

It is known that a 20- to 60-pound per acre application of sulphur in a soluble sulphate form will overcome the deficiency on the Loon River soil for at least 2 years (2). That such a small application is sufficient to allow for leaching and other losses and still provide sufficient sulphur to the crop indicates that the sulphur balance is delicate and that even a slight amount of barium in solution could contribute to the deficiency.

The Garrick soil has several characteristics that the Loon River soil lacks to offset any possible effects of barium: (a) it is relatively well provided with calcium; (b) it is well buffered; (c) it contains a plentiful supply of soluble sulphate at a shallow depth; and (d) it contains a substantial quantity of organic matter that, on decomposition, may have the same solubilization effect on forms of sulphur as on relatively insoluble forms of phosphorus (9). 'Sorption' of SO_4 within soil in an acid medium has been reported by Wiklander (16) but no information is available on the barium status of the soil within which the precipitation occurred. It is thus impossible to relate the results of the present study to those of the study reported. The results of the present study do not prove that barium

is active under field conditions, but simply point to the possibility.

The two soils differ markedly in the C horizon. The Garrick soil contains more than three times as much sulphur as the Loon River in this horizon. The C horizon of the Loon River soil precipitated sulphate-sulphur and released approximately the same quantity of sulphur to an acid or near-neutral extractant indicating the presence of barium in this horizon also. There was no tendency for the C horizon of the Garrick soil to precipitate sulphate, and considerably more sulphate-sulphur was extracted with acid than near-neutral extractants, indicating the absence of barium and the presence of calcium sulphate. These findings were borne out by the results of spectrogramming samples of the C horizon of the two soils. Since roots could readily penetrate to this source of sulphur, the nature of, and depth to the C horizon would seem to be factors worth considering in the detection of a sulphur deficiency.

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THE INFLUENCE OF SOIL TEMPERATURE ON THE GROWTH AND MINERAL COMPOSITION OF OATS[1]

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ABSTRACT

Oats grown with different nutrient treatments in temperature-controlled soil in the greenhouse produced higher yields of grain and straw when soil temperature was increased from 41° to 67°F. Yields were usually less at 80°F. than at 41°F. This relationship between growth and soil temperature was also apparent at the heading stage. At 7th leaf, however, the best temperature for growth varied with nutrient treatment. Root yields usually decreased with increase in soil temperature.

Increasing soil temperature from 41° to 67°F. increased uptake of N, P and K. In many instances increases in the concentration of N, P and K in the plant contributed to these increases in uptake. The effect of soil temperature on uptake was more consistent for P than for other elements.

Nitrates and native phosphorus in incubated soil samples increased with increase in temperature from 41° to 80°F. but exchangeable K values were not affected.

INTRODUCTION

It is common experience that crop yields in field fertilizer trials may vary considerably from year to year even on the same site and under the same management. In seeking a better understanding of these variations, it was considered advisable to investigate the influence of soil environment on yield and mineral composition of crops. Initially, consideration was given to soil temperature. In an extensive review of work on effects of soil temperature on plant growth, Richards, Hagan and McCalla (11) suggested that there was a scarcity of well-designed experiments on the subject.

The results presented herein relate to the effect of soil temperature on growth and mineral composition of oat plants harvested at different stages of maturity in the greenhouse. A few data on the effect of temperature on the availability of nitrogen, phosphorus, and potassium in the soil are included.

MATERIALS AND METHODS

The soil used was Castor silt loam (4) with the following properties: pH-7.1, organic matter – 1.91 per cent, total nitrogen – 0.07 per cent, and base exchange capacity – 7.2 m.e./100 gm.

For the greenhouse test, krilium was added to the soil at the rate of 0.1 per cent. Ten pounds of air-dried treated soil were placed in glazed gallon pots. The nutrient treatments were PK, NK, NP and NPK. These were mixed throughout the soil at rates of 75 pounds N, 200 pounds P_2O_5, and 200 pounds K_2O per acre. Soil moisture was adjusted with distilled water to approximately field capacity. Oats were seeded and later thinned to 10 plants per pot.

At the 5th leaf stage of growth the pots were placed in temperature baths which were maintained at 41°, 54°, 67° and 80°F. (3) for the remainder of the growth period. The experiment was conducted in five

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TABLE 1. — YIELD OF OATS AT DIFFERENT SOIL TEMPERATURES
(Average of three replicates)

Nutrients added	Soil temperature	Top growth at different stages				Root growth at different stages		
		7th leaf*	Heading	Mature		7th leaf*	Heading	Mature
				Straw	Grain			
	°F.	gm. dry matter/pot				gm. dry matter/pot		
PK	41	5.5	9.2	9.2	4.1	7.8	11.7	6.4
	54	6.2	9.7	9.4	5.7	5.1	6.4	3.6
	67	6.3	10.9	9.9	5.9	2.6	5.4	1.4
	80	5.4	8.3	8.0	3.7	2.2	3.2	0.8
NK	41	2.8	4.7	5.2	2.1	2.1	2.9	2.2
	54	3.2	6.1	6.5	3.4	2.4	2.0	2.2
	67	3.8	6.4	9.2	4.7	1.5	2.5	1.6
	80	4.2	5.0	5.1	2.2	1.3	1.3	0.8
NP	41	6.3	11.8	11.6	6.6	6.6	9.2	4.8
	54	5.5	12.2	11.9	8.4	4.7	8.7	2.9
	67	5.5	13.0	12.0	8.6	3.8	3.4	1.4
	80	4.9	8.7	8.5	2.1	2.1	1.6	0.8
NPK	41	6.1	12.3	12.8	8.9	3.2	7.1	4.6
	54	5.4	13.4	13.2	9.4	3.6	7.4	3.1
	67	5.4	13.0	13.4	10.3	4.7	5.9	1.4
	80	5.2	9.9	11.1	3.7	2.7	1.8	0.9

*The plants were subjected to different soil temperatures from 5th leaf stage to maturity. At the 5th leaf stage yields were 1.8, 1.4, 2.0, and 1.9 grams of tops and 0.9, 2.7, 1.2, and 2.1 grams of roots for the PK, NK, NP, and NPK treatments, respectively.

series seeded at the same time, but harvested at the following stages of growth: 5th leaf, 7th leaf, heading, soft dough, and maturity. The nutrient treatments were randomized and replicated three times in each of the temperature baths, but there was no replication of temperature. Soil moisture was maintained at approximately field capacity by adding the required amount of water as determined by weighing the pots. Both tops and roots were taken at each harvest. The roots were separated from the bulk of the soil and washed. The tissues were dried and ground in a Wiley mill.

The material was ashed in the muffle at 500°C. The ash was treated according to the procedure of Peech *et al.* (10) except that the residue was dissolved and made to volume with 0.2 N HCl in preparation for analysis. Phosphorus was determined by the method of King (6) and calcium as described by Peech *et al.* (10). After separation of the calcium, magnesium was titrated with versene (2). Potassium was determined with a Model 146 Perkin-Elmer flame photometer using lithium as an internal standard. Total nitrogen in the samples was estimated by the Kjeldahl-Gunning-Arnold method (1).

To assess the effect of temperature on the availability of nitrogen, phosphorus, and potassium in the soil, samples were incubated for 7 months in the temperature baths controlled at 41°, 54°, 67° and 80°F. Soil moisture was maintained at approximately field capacity by additions of water as required. Following incubation, samples were air dried, and passed through a 2-mm. sieve. Nitrate nitrogen was determined by the procedure of Metson (8) and phosphorus by that of Olsen *et al.* (9). Exchangeable potassium was extracted with ammonium acetate (10) and measured by flame photometry.

RESULTS AND DISCUSSION

Yields of Oats

The yields of roots and tops of oats harvested at 7th leaf, heading, and maturity are presented in Table 1. Data for a soft dough stage were omitted from the table since yield trends were similar to those at heading stage. Since there was no replication of temperature the data were not treated statistically.

Addition of phosphorus (NK vs. NPK) usually resulted in pronounced increases in yield of tops and roots. The magnitude of these increases tended to be less with increase in temperature. Nitrogen (PK vs. NPK) and to a lesser extent potassium (NP vs. NPK) had a beneficial effect on yield of tops at heading and maturity but there was no consistent effect on root yields.

At heading and maturity, yields of foliage or grain and straw increased almost invariably with increase in soil temperature to 67°F. regardless of nutrient treatment. With a further increase in temperature to 80°F., yields were usually lower than at 41°F. There was a tendency (NP, NPK treatments) for yield of grain relative to straw to be depressed at 80°F. In contrast to the above results, yields of foliage at the 7th leaf stage were highest at 41°F. when nitrogen and phosphorus were both added.

At all stages of harvest there were trends for root yields to decrease with increase in temperature. While yields of foliage increased with advancing stage of growth, yields of roots increased from 7th leaf to

TABLE 2.—EFFECT OF SOIL TEMPERATURE ON TOP: ROOT RATIO OF OATS

Nutrients added	Soil temp.	Top: root ratio at different stages		
		7th leaf	Heading	Mature
	°F.			
PK	41	0.7	0.8	2.1
	54	1.2	1.5	4.2
	67	2.4	2.0	11.3
	80	2.5	2.6	14.6
NK	41	1.3	1.6	3.3
	54	1.3	3.0	4.5
	67	2.5	2.6	8.7
	80	3.2	3.8	9.1
NP	41	1.0	1.3	3.8
	54	1.2	1.4	7.0
	67	1.4	3.8	14.7
	80	2.3	5.4	13.3
NPK	41	1.9	1.7	4.7
	54	1.5	1.8	7.3
	67	1.1	2.2	16.9
	80	1.9	5.5	16.4

TABLE 3.—NITROGEN CONTENT OF OAT TOPS
(Average of three replicates)

Nutrients added	Soil temperature	Stage of growth			
		7th leaf	Heading	Mature	
				Straw	Grain
	°F.	%	%	%	%
PK	41	2.0	1.2	0.5	2.2
	54	1.9	1.4	0.4	1.6
	67	2.1	1.5	0.3	2.2
	80	2.7	1.8	0.5	3.0
NK	41	2.4	1.8	0.9	3.3
	54	3.1	2.3	1.0	3.1
	67	3.2	2.5	1.0	—
	80	3.1	2.6	1.1	3.5
NP	41	3.0	1.8	0.5	2.7
	54	3.9	1.9	0.5	2.5
	67	3.8	2.1	0.5	2.6
	80	3.9	2.5	1.4	3.4
NPK	41	3.2	1.9	0.4	2.5
	54	3.9	2.0	0.4	2.4
	67	3.9	2.1	0.5	2.5
	80	3.9	2.4	1.2	3.3

heading but decreased from the latter stage to maturity. The different growth behaviour of foliage and roots is shown by the trends for increase in top: root ratios with increase in temperature and with advancing stage of growth (Table 2).

Mineral Composition

Analyses indicated that root samples were contaminated with soil and for this reason composition data are presented for tops only.

Nitrogen – Table 3 shows that the concentration of nitrogen in oats tended to increase with increase in temperature. Nitrogen in the plants at heading increased consistently with increase in temperature, and up to 67°F. the increase in content was associated with increase in yield (Table 1). In most instances addition of nitrogen (PK vs. NPK) increased nitrogen content of plants. At the 7th leaf stage, addition of phosphorus (NK vs. NPK) increased absorption of nitrogen as indicated by simultaneous increase in yield and content. Evidently, at this stage the plants were able to assimilate more nitrogen when the supply of phosphorus was improved.

Phosphorus – There were trends for the concentration of phosphorus in the plants to increase with increasing temperature (Table 4). These trends accompanied corresponding yield trends up to 67°F. except for the NP and NPK treatments at 7th leaf. Thus, the increase in per cent phosphorus with increase in temperature could not be ascribed to dilution in the plant. Per cent phosphorus increased with addition of phosphorus except in the straw (NK vs. NPK). It was usually highest when nitrogen

TABLE 4.—PHOSPHORUS CONTENT OF OAT TOPS
(Average of three replicates)

Nutrient added	Soil temperature	Stage of growth			
		7th leaf	Heading	Mature	
				Straw	Grain
	°F.	%	%	%	%
PK	41	0.31	0.24	0.14	0.44
	54	.38	.30	.13	.46
	67	.44	.34	.18	.42
	80	.43	.36	.23	.51
NK	41	.10	.07	.04	.23
	54	.16	.12	.04	.28
	67	.21	.16	.07	.34
	80	.27	.24	.05	.36
NP	41	.22	.18	.05	.34
	54	.34	.22	.03	.41
	67	.38	.27	.04	.44
	80	.36	.24	.09	.53
NPK	41	.22	.17	.04	.35
	54	.29	.22	.03	.40
	67	.34	.25	.04	.44
	80	.37	.25	.07	.50

TABLE 5. — CATION CONTENT OF OAT TOPS
(Average of three replicates)

Nutrients added	Soil temperature	Stage of growth											
		7th leaf			Heading			Mature					
								Straw			Grain		
		Ca	Mg	K	Ca	Mg	K	Ca	Mg	K	Ca	Mg	K
	°F.	me. / 100 gm.											
PK	41	33	30	93	27	22	72	35	25	75	7	16	12
	54	30	28	109	26	22	83	32	25	83	8	20	12
	67	29	29	109	22	22	84	34	29	80	7	17	11
	80	32	33	119	26	27	91	31	32	88	8	20	15
NK	41	26	20	115	24	19	87	32	33	92	8	14	13
	54	24	23	138	22	21	108	28	28	95	8	16	13
	67	29	28	123	23	23	97	27	31	97	14	23	13
	80	29	28	115	27	28	82	48	38	108	10	19	11
NP	41	39	33	27	32	26	25	44	39	25	8	15	12
	54	36	33	39	29	30	34	43	39	30	9	18	11
	67	35	47	49	28	34	33	41	53	32	8	17	13
	80	37	50	47	33	32	37	49	47	34	10	20	14
NPK	41	37	29	98	30	21	67	38	23	59	8	15	14
	54	35	29	113	29	24	76	35	29	59	9	18	14
	67	33	28	116	24	24	73	34	31	65	7	17	12
	80	41	41	128	32	29	84	44	40	78	8	19	16

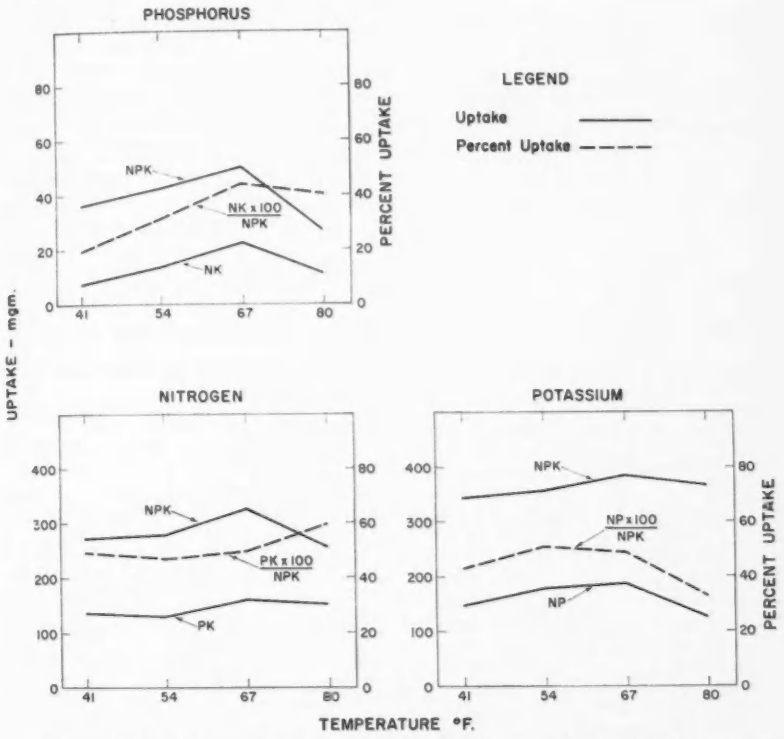

FIGURE 1. Total absorption of nitrogen, phosphorus and potassium by oats at maturity.

was omitted from the nutrient treatment. This depressive effect of nitrogen on per cent phosphorus could not always be attributed to just an increase in yield of dry matter. For example, at 7th leaf stage the yields with NPK treatment were lower than those obtained with PK except at 41°F.

Cations — Data in Table 5 show magnesium and potassium contents tended to increase with increase in soil temperature. There was a tendency for the calcium content to decrease with increasing temperature to 67°F. and then to rise at 80°F. Thus, calcium tended to vary inversely with yield whereas magnesium and potassium tended to increase along with yield when soil temperature was increased to 67°F. With addition of potassium (NP vs. NPK) increases in potassium content were usually accompanied by decreases in calcium and magnesium. The slightly higher Ca:Mg ratios for the NPK than for the NP treatment (Table 6) indicate that potassium had a more depressive effect on magnesium than on calcium. The lower Ca:Mg ratios at 67°F. than at 41°F. reflect the tendency of the magnesium concentration to increase with increase in temperature. The total equivalents of cations increased with addition of potassium and with increase in temperature.

TABLE 6.—CATION RATIOS AND TOTAL CATIONS IN OAT TOPS AT HEADING STAGE

Soil temperature	Cation equivalent ratios						Sum of cations (Ca+Mg+K)	
	Ca:Mg		Ca:K		Mg:K			
	NP	NPK	NP	NPK	NP	NPK	NP	NPK
°F.							me./100 gm.	
41	1.2	1.4	1.3	0.4	1.0	0.3	83	118
54	1.0	1.2	0.9	0.4	0.9	0.3	93	129
67	0.8	1.0	0.9	0.3	1.0	0.3	95	121
80	1.0	1.1	0.9	0.4	0.9	0.3	102	145

TABLE 7. — INFLUENCE OF SOIL TEMPERATURE ON AVAILABILITY OF NITROGEN, PHOSPHORUS, AND POTASSIUM IN CASTOR SILT LOAM

Soil temperature	Nitrates (N)	$NaHCO_3$–soluble P	Exchangeable K
°F.	p.p.m.	p.p.m.	me./100 gm.
41	35	5.2	0.07
54	36	5.6	.07
67	41	6.0	.06
80	62	6.5	.07

Total Absorption of Nutrients

The amounts of elements removed by plant tops were computed from yield and composition data. The amounts removed at each stage of growth, when expressed as percentages of amounts removed at maturity, were found to vary somewhat with temperature and nutrient treatment. At a particular stage, the percentage removal of nitrogen and phosphorus was usually highest when the soil temperature was 80°F. At soil temperatures up to 67°F., omission of phosphorus (NK) tended to reduce percentage removal of nitrogen, phosphorus and potassium at all stages before maturity.

Figure 1 shows that the amounts of nitrogen, phosphorus, and potassium removed by oats at maturity were highest when the soil temperature was 67°F. Evidently, the best soil temperature for top growth (67°F.) was more favourable for absorption of these elements than were lower temperatures. The increase in uptake of phosphorus with increase in temperature to 67°F. was particularly marked and was reflected in both yield and content. The per cent uptake values in the graphs show that the amount of phosphorus supplied by the soil, relative to that taken up with NPK treatment, increased with increase in temperature to 67°F. The per cent uptake values for nitrogen and potassium in relation to temperature were less consistent.

The increase in phosphorus uptake with increase in temperature to 67°F. is in agreement with results for other crops as reported by other workers (5, 7, 12). The greater availability of soil nitrogen and phosphorus

with increasing temperature (Table 7) would favour uptake of these elements. But the effect of temperature on uptake was also apparent when NPK treatment was used to minimize the differences in nutrient supply. Shtrausberg (12) found that uptake of phosphorus by oats in water cultures was greater at 69.8°F. than at 44.6°F. In the reported work, temperature may have had a direct effect on absorption of nutrients by the roots, or it may be that the effects were indirect and associated with the marked differences in growth habits of the plants grown at different soil temperatures.

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RELATIONSHIP OF THE PERMANENT WILTING PERCENTAGE AND THE SOIL MOISTURE CONTENT AT HARVEST TO THE 15-ATMOSPHERE PERCENTAGE

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ABSTRACT

Permanent wilting percentages based on the wilting of the upper leaves of sunflower plants were related to the 15-atmosphere percentage by the equation PWP = 0.35 + 0.833 FAP. This wilting percentage, which was lower than that based on a mean wilting condition of the plant as a whole, provided satisfactory estimates of minimum soil moisture contents under cereal crops at harvest time.

INTRODUCTION

The pressure membrane apparatus has become standard equipment in most soil laboratories and the 15-atmosphere percentage is used by many workers as the limiting moisture content below which water cannot be used by crops. This minimum moisture or permanent wilting percentage is required by plant and soil scientists to convert total soil moisture content to moisture available for plant growth. Likewise, the difference between permanent wilting percentage and field capacity gives the available moisture-holding capacity of soils.

Furr and Reeve (2) found a wide range of moisture content between what they called the first permanent wilting percentage, which is indicated by the wilting of the lower leaves of sunflower plants, and the ultimate wilting percentage indicated by the wilting of the top leaves. They showed that the wilting range between these two extremes comprised 11 to 30 per cent of the total available moisture.

Different workers used different degrees of wilting to determine the direct wilting percentage with sunflowers. Briggs and Shantz (1) used the early stage of wilting which corresponded to the first permanent wilting percentage of Furr and Reeve. Taylor, Blaney, and McLaughlin (10) and Staple and Lehane (8) used the wilting of upper leaves which was more comparable to the ultimate wilting percentage. Veihmeyer and Hendrickson (11) and Work and Lewis (13) used an intermediate stage of wilting. With sufficient replication the wilting percentage obtained by any one group of workers was reproducible, but it varied with the different wilting symptoms used.

Richards and Weaver (5) found that, for 64 out of 71 soils, the 15-atmosphere percentage fell between the first and ultimate wilting percentage of Furr and Reeve. In a more recent summary Richards and Wadleigh (7) obtained the relation PWP = 0.85 + 0.96 FAP using weighted values for 199 soils. They also showed that the first permanent wilting of Furr and Reeve was FPWP = 1.50 + 1.022 FAP and the ultimate wilting percentage UWP = 0.36 + 0.863 FAP.

Recently Wilcox (12) obtained the relationship PWP = –0.662 + 1.016 FAP, based on permanent wilting of the first two true leaves of the sunflower plant.

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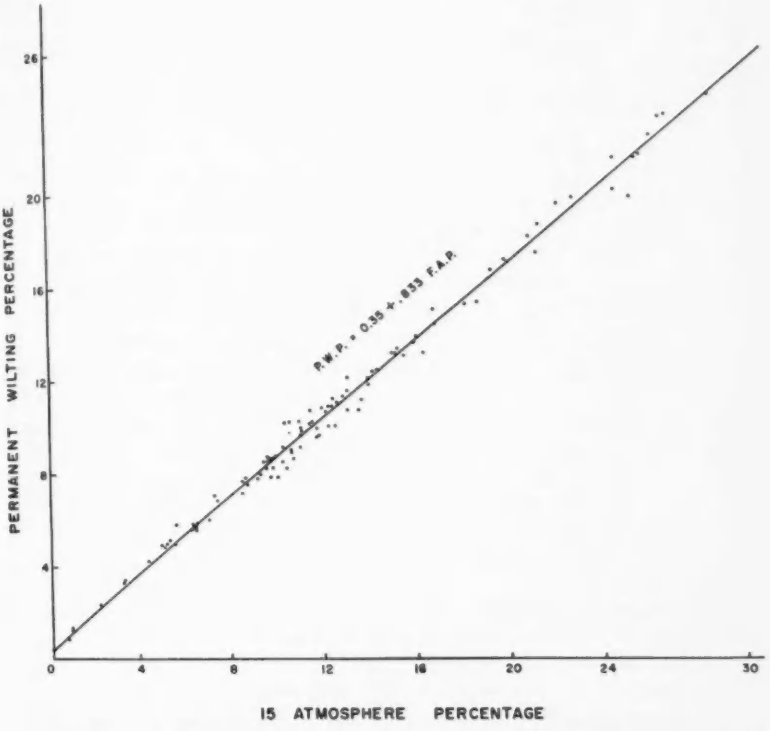

FIGURE 1. The relationship between permanent wilting percentage and 15-atmosphere percentage.

The purpose of the present paper is to show the relationship between the permanent wilting percentage obtained at this laboratory and the 15-atmosphere percentage. This permits comparison of the pressure membrane method of indirect wilting point determination with the desiccator method described previously (4). The soil moisture content found under cereal crops at harvest time is also compared with the 15-atmosphere percentage and with the corresponding estimate of permanent wilting percentage.

METHODS

Permanent wilting percentages were determined by the direct method of growing dwarf sunflowers as outlined by Work and Lewis (13). The wilting of the upper leaves of the sunflower plant was used to indicate wilting. These determinations were made in connection with previous experiments, and the stored samples were used for pressure membrane measurements in the present work.

Determinations of the 15-atmosphere percentage were made with Richards' (6) pressure membrane apparatus. The soil was passed through

a 2-mm. sieve, placed in rings without packing, saturated for 24 hours, and held under 15-atmosphere pressure for another 48 hours at a temperature of approximately 68°F.

Fifteen-atmosphere percentages were determined also on field samples taken at harvest time in 1958 and 1959. These samples were taken primarily for soil moisture determination in sections 0 to 6, 6 to 12, 12 to 24, 24 to 36, and 36 to 48 inches with 6 to 13 borings from each site. The moisture content was found in per cent of oven-dry weight and this was converted to inches of water, using the requisite bulk density for each depth of soil. The bulk densities were obtained for each site from cores of undisturbed soil 2.5 inches in diameter and 2.5 inches high. Composite samples for each depth at each site were used for the 15-atmosphere determination.

RESULTS

Figure 1 shows the relationship between the permanent wilting percentage and the 15-atmosphere percentage for 99 samples of soil covering a range of textures. The wilting percentages were the average of eight replicates which had a standard deviation of 0.54 per cent. The 15-atmosphere values were the average of three runs, with standard deviation of 0.34 per cent. The regression equation was PWP = 0.35 + 0.833 FAP with a correlation coefficient of 0.995. This equation is quite close to that for ultimate wilting attributed to Furr and Reeve by Richards and Wadleigh (7). Comparison of the regression equations indicates that wilting percentages based on the upper leaves are approximately 87 per cent of the mean values reported by Richards and Wadleigh.

Soil moisture contents at different depths in wheat fields at harvest time, 1958 and 1959, are plotted against the 15-atmosphere percentage in Figure 2. Data for the 0-to-6-inch layer were omitted because evaporation usually reduces the moisture content of the surface soil to below the wilting point at harvest. The 45° line shows what the harvest moisture would be if it coincided exactly with the 15-atmosphere percentage. The permanent wilting percentage corresponding to the regression equation is given by the broken lines.

Figure 2 shows that the harvest moisture contents at 6- to 12-inch and 12- to 24-inch depths were lower than both the 15-atmosphere and the permanent wilting percentage. The moisture in the 24- to 36-inch depth was approximately equal to, and that in the 36- to 48-inch depth was higher than, the wilting percentage. These data, brought together in Table 1 for the 4-foot profile, show that the harvest moisture content was approximately equal to the permanent wilting percentage, but it was considerably lower than the 15-atmosphere percentage. The average field moisture at harvest time was 0.33, 0.96, and 2.01 inches of water less than the moisture held at the 15-atmosphere tension for coarse, medium, and fine-textured soils respectively.

DISCUSSION

The permanent wilting percentage is correlated equally well with both the 15-atmosphere percentage and the wilting percentage estimated by the desiccator method (4). The two methods of indirect wilting point

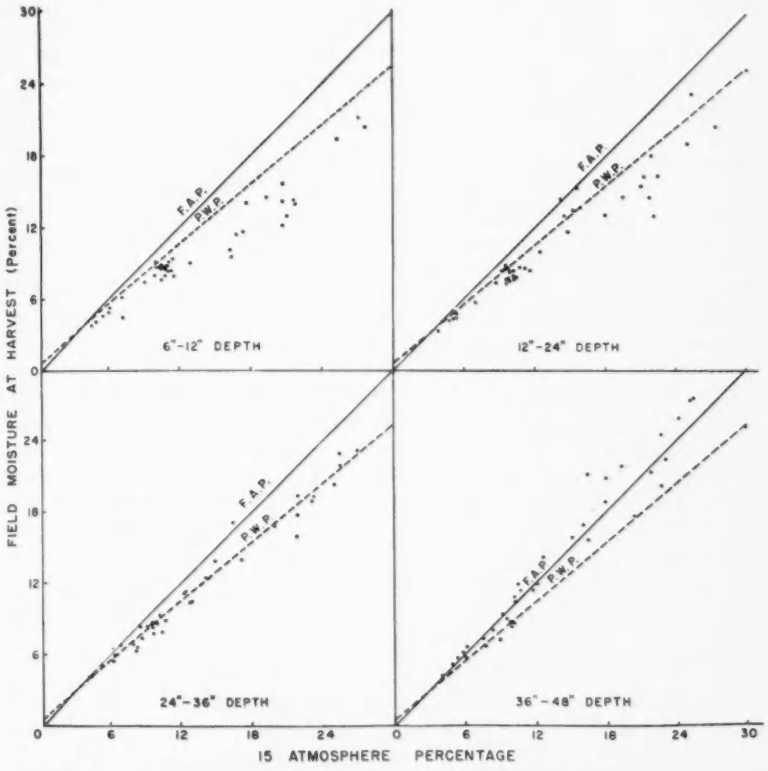

FIGURE 2. The relation between field moisture content at harvest and 15-atmosphere percentage. The broken line represents the computed permanent wilting percentage.

determination involve nearly equal amounts of labour, but the time required for soil to approach equilibrium is sometimes objectionable in the desiccator method. The pressure membrane should be used where large numbers of samples are handled. The dessicator method may still be useful in small laboratories where the volume of samples does not justify the more expensive pressure membrane apparatus.

The desiccator method was based on the moisture absorbed by a soil in an atmosphere of controlled humidity during a 14-day period. Minor fluctuations in absorption were corrected for in each determination by using a standard sample of known wilting point. The results given by the desiccator method depend on the degree of wilting used in calibrating the standard sample.

Under dryland farming conditions in southern Saskatchewan, cereal crops remove moisture to approximately the same level each year. The scatter shown in Figure 2 is due largely to plant and climatic conditions. A short, thin crop may remove the moisture to a lesser extent than a tall,

TABLE 1.—COMPARISON OF THE FIELD MOISTURE AT HARVEST (1958 AND 1959) WITH THE 15-ATMOSPHERE AND THE PERMANENT WILTING PERCENTAGE IN A 4-FOOT PROFILE

Site No.	Field moisture at harvest	15-atmosphere percentage	Calculated PWP
	inches	inches	inches
		Sandy Loam	
1	3.64	4.09	3.76
2	3.96	4.37	3.99
3	3.22	3.60	3.35
4	4.14	4.33	3.96
5	3.95	4.25	3.89
6	3.84	4.07	3.74
Average	3.79	4.12	3.78
		Clay	
7	9.84	10.71	9.27
8	8.98	11.36	9.81
9	10.67	12.65	10.89
10	10.18	12.42	10.70
11	12.84	13.84	11.90
12	12.48	14.12	12.11
13	10.26	11.81	10.19
14	10.02	12.52	10.78
15	9.89	12.74	10.96
16	9.34	12.82	11.03
17	11.60	13.01	11.19
18	10.92	13.07	11.24
Average	10.59	12.60	10.84
		Loams and Clay Loams	
19	5.48	6.38	5.66
20	5.35	6.24	5.55
21	5.67	6.41	5.69
22	5.09	6.06	5.40
23	5.81	6.72	5.95
24	6.01	6.67	5.91
25	5.21	6.24	5.55
26	5.59	6.20	5.52
27	5.05	6.05	5.40
28	5.62	6.00	5.35
29	4.84	5.90	4.38
30	4.66	6.09	5.45
31	6.26	7.23	6.37
32	6.68	7.42	6.55
33	6.30	7.54	6.65
34	6.34	7.29	6.45
35	6.72	7.40	6.55
36	5.86	6.93	5.80
37	5.00	5.94	4.96
38	5.40	7.02	6.20
39	5.82	7.31	6.44
Average	5.66	6.62	5.80

thick one. Crops that are subjected to high temperatures for a period of a week or more during the later stages of growth may be unable to extract moisture from lower depths. Heavy rains before harvest sometimes cause moisture to be left in the root zone. The seasons of 1958 and 1959 were dry so that crops were grown under continual soil moisture stress. Con-

ditions were not severe enough, however, to interfere greatly with root development or the removal of moisture from the root zone.

Hendrickson and Veihmeyer (3) found that the minimum moisture at harvest was approximately equivalent to the permanent wilting percentage but higher than the ultimate wilting percentage described by Furr and Reeve (2). The latter authors stated that the moisture within the wilting range provided the plant with an emergency reservoir that enabled many species of plants to survive periods of prolonged drought or to mature seed after vegetative growth had ceased. Staple and Lehane (8) found that wheat plants could use some moisture below their permanent wilting percentage, and pointed out that, even if vegetative growth stops near the wilting percentage, it does not mean that further reduction is a total loss. They believed that such moisture was important to the yield and quality of grain. The observations of different workers indicate that the limit of available moisture is probably different for different types of crop. For instance, fruits, vegetables or forage crops may not be able to extract moisture from soil at as high a moisture deficit as can a maturing wheat crop. These limitations of the concept of a constant permanent wilting percentage for each soil are well known (9). Fortunately a useful experimental value can be found for different crops and growing conditions.

The present work confirms that soil moisture is reduced to below the permanent wilting percentage at some depths at harvest. In most years, however, as shown in Table 1, the permanent wilting percentage, as determined at Swift Current, is satisfactory for obtaining available moisture in the 4-foot root zone of cereal crops in semi-arid areas. It can be computed from the 15-atmosphere percentage using the equation $PWP = 0.35 + 0.833$ FAP.

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